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RESEARCH ISSUES IN IMPLEMENTING REMOTE PRESENCE IN TELEOPERATOR CONTROL

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SUMMARY

This is a position paper introducing the concept of remote presence in telemanipulation. Remote presence or telepresence is a property of an intimate man/machine interface in which the human operator is provided with a simulated sense of physical presence at the remote task site. It is suggested as an alternative to supervisory control for optimizing performance. Evidence is cited to support the contention that enhancement of a sense of presence will improve performance. A conceptual design of a prototype teleoperator system incorporating remote presence is described. The design is presented in functional terms of sensor, display, and control subsystems. The concept of an intermediate environment, in which the human operator is made to feel present, is explicated. The intermediate environment differs from the task environment due to the quantity and type of information presented to an operator and due to scaling factors protecting the operator from the hazards of the task environment. Several research issues pertaining to the development of a telepresent manipulator are delineated. The potential benefits of remote presence systems, both for manipulation and for the study of human cognition and perception are discussed.

INTRODUCTION

Remote manipulators, or teleoperators, are devices designed to allow the performance of manipulative tasks in environments that are either too hostile or too remote to permit the physical presence of a human being. Situations in which use of remote manipulators may be appropriate include handling of highly radioactive materials and construction or exploration in space or undersea environments.

Recently efforts have been made to make the human operator (HO) of the device remote not only from the environment of the manipulation task, but also from direct control of the actual manipulations. The HO is increasingly being placed in a supervisory or "higher level" control loop (1). The trend to define the operator's function as that of supervisory controller has been based on a combination of physical constraints and assumptions concerning human performance. The HO in direct control of a remote manipulator, equipped with industry standard visual and end point displayed force reflecting feedback and vise-like grip , does not perform remote manipulation tasks as accurately or as quickly as those tasks performed by direct hands-on manipulation (2,3). The assumption is that a semi- or completely automated sensor or algorithm driven manipulator could surpass the HO performance. The physical or psychomotor constraints requiring supervisory control are ennunciated by Ferrell and Sheridan (4):

a) the HO is so physically removed from the device as to cause inherent time delays in the control or feedback loop due to transmission lags. Such transmission lags could also be introduced in cases where a hostile environment necessitated bandwidth limitations on feed forward or feedback transmission,

b) the operator is overburdened with other control or decision tasks.

c) the operator is prevented from exercising direct control, either due to environmental constraints of space limitations or as a result of physical handicap, as in the case of quadriplegia.

Under many conditions physical or psychomotor constraints are not the limiting factor. If the allocation of supervisory function is based on previous performance deficits or on HO overburdening resultant from inappropriately displayed information, we contend that the operator should be placed in direct control of the remote manipulator. Rather than removing the operator from the control loop efforts should be made to more tightly couple the HO and the manipulator.

The performance values of the HO should be exploited. The HO is adaptive and able to respond to anomaly. The operator's neuromuscular response provides for rapid, varied and fine control of manipulation. Direct control serves to reduce computational costs both in time and range of function. Finally, tasks performed in an environment whose characteristics are unstructured or unknown (and given the state of the art of computational intelligence) require that the HO be relied on for control.

METHOD

We have noted that in present systems the HO displays poor performance when in direct control of a remote manipulator. This method of control is currently characterized by limited or inappropriately coded information to the HO and by a technical subsytem of limited dexterity. We contend that this deficit is a function of the method by which control is effected rather than an inherent limitation of the HO in the performance of the task.

Examination of the literature (5) has led us to the conclusion that tightening the loop between the operator and effector will provide adequate to superior performance in manipulation. The conclusion is supported by three lines of evidence.

1) As previously reviewed, the supervisory control paradigm is appropriate when a tight link between operator and effector cannot be maintained. Such an approach is necessitated by the fact that continuous control is not possible if the HO/effector time lag increases beyond the HO's reaction time (6).
2) Physiological research in neuromuscular control indicates that tight sensory motor integration is necessary for functional motor control (7, 8, 9, 10).
3) Inference from previous research indicates that

as the link between operator and manipulator is tightened performace improves. Master slave mechanical linkage with force reflecting feedback improved performance (11). Tight mechanical link with the effector improves performance (12).

We propose that the operator/effector link can be tightened through the development of high fidelity sensors, integrated displays, true master slave control incorporating multiarticulated end effectors, and appropriate transformation algorithms. Consideration of the conceptual design parameters and recommended development for each of these subsystems follows.

CONCEPTUAL DESIGN

Figure 1 represents a potential conceptual design for a telepresent manipulation system. The arm is designed to be a position feedback system with force proportional control. A review of the state of the art of the subsytems indicated has recently been made (5) and will not be detailed here. The subsystems will be reviewed with attention to the requirements of an effective man/machine interface and to the research issues which need to be addressed for system realization.

Sensor Subsystem.

The sensor subsytem of the proposed advanced manipulator system serves the dual function of sensing operator input and commands through the master arm and sensing the condition of the remote arm, including environmental influences on that arm.

Position sensors referencing the condition of the master arm are well within the state of the art. We have in Figure 2 indicated that a simple rotary potentiometer is sufficient to provide the necessary control information.

A more challenging aspect of the sensor subsystem are those sensors which are to provide information about the remote arm and the environment in which it is operating. Several types of sensors in several modalities are suggested. Tactile information, including touch, slip, and pressure is required. Several technologies have developed which may provide the necessary capabilities. They have been reviewed in detail by Harmon (13). Strain gauges (14) have been considered. Pressure sensitive materials (15) have been tested. Hill and Bliss (16) have tested a polymer switch arrangement in manipulator control. Bejczy (17, 18) has developed many of the advanced tactile sensor systems which would be useful in manipulator control, including touch sensors, pressure sensors and directional slip sensors. This sensory information is to be used to drive a distributed and veridical display to the operator. It is suggested that the sensor density follow roughly the human sensitivity to these inputs, with highest density sensor distribution in the end effector and a significant reduction in density for the more proximal portions of the manipulator.

Information regarding the forces impinging on the manipulator and end effector must be transmitted to the operator for proper control. These forces must be sensed on the manipulator and localized in terms of their directon and magnitude. Judiciously placed strain guages, for example, are well suited to this task.

Sensor Research Issues

Sensors used to characterize a hostile environment must be shielded from that environment wihtout loss of sensitivity to changes in environmental conditions. Such selective ruggedization of sensors must be explored. Recent experience indicates that it is possible that as analogs of biological systems are developed, they will be as prone to failure, in the same situation, as their living counterparts.

Another issue for investigation is determination of the type of sensory information most useful to the operator. This issue is highly interactive with display capabilites. Our design suggests incorporation of as many sensory modalities as possible.

Display Subsystem

Of significantly greater difficulty than acquiring tactile and proprioceptive information is effectively displaying it to the operator. Proprioceptive information should be displayed to the HO as a distributed function with torques felt about the appropriate axes of rotation. If the load is at the endpoint of the manipulator, as in hand grip, then loading should be displayed to the hand of the operator. If, on the other hand, the loading is distributed over the entire surface of the manipulator, as in large load lifting or encounter with distributed resistance, the loading must be displayed over the relevant surfaces of the operator's arm. The current procedure of localizing all feedback at the wrist imposes a cognitive load in force translation and a fatiguing physical load at the operator's wrist. An exoskeltal position feedback system is suggested to provide distributed proprioceptive information. The distributed surface pressure display (Figure 4) responds to surface sensor activity at the remote location. The display will provide distributed touch sensing ability to the operator. In addition the sleeve provides for temperature display via hydraulic chambers responsive to temperature sensors at the remote site.

Tactile information has classsically been displayed via mechanical stimulation through vibrotactile transducers. Vibrotactile stimulation has been induced by airjets, piezoelectric vibratory elements, electromagnetic and electromechanical stimulation (16, 19, 20). Electrocutaneous stimulation has been explored (21). Electrocutaneous stimulation can be used to provide sensations of pressure, pain and heat. Flexibility of stimulation parameters, portability, and increasing miniaturization potential recommend electrotactile information display.

Display Research Issues

Both electrotactile and vibrotactile stimualtion share certain research issues which constellate around questions of:

- How accurately does the sensation provided mimic natural stimulation?
- How do the percieved attributes of the sensation vary as a function of body site stimulated?
- What is the optimal display density and

distribution?

In addition to the more common display issues there are several psychophysical interactions which could be exploited in the effective presentation of electrotactile stimulation. Structural interactions provide stability and accuracy in the inherently noisy neural systems. For example, lateral inhibition in the retina is a process of local inhibition of receptors as a function of stimulation intensity. This inhibition provides a sharpening of the illumination difference among the receptors. The result is a perceptual demarcation of stimulus intensity change that has no physical corollary in the stimulus. The sharpening of tactile stimuli by the simulation of the biological transduction process of structural interaction has been initiated (22). Temporal interactions in tactile display also provide an ability to exploit physiological processing. Sensory saltation (23) and the "phi phenomenon" (24) both, through appropriate stimulation sequencing, provide stable tactile stimulation which is not associated with a particular stimulator site. These processes suggest methods of increasing display density without a cost in operator encumbrance.

Control Subsystem

The control system is intended , as illustrated in Figures 2 and 3a,b,c, to be a fully articulated master slave control. The master slave control concept is likely to maintain the tight link between operator and manipulator which is necessary to generate a sense of presence. The computational requirements in the master slave controller should be significantly lower than other types of controllers.

Control Research Issues

The integration of several interactive feedback and feedforward loops which is required in our design raises some issues asociated with control stability. It is imperative that the operator control link be maintained as tightly as possible so as to minimize control lags and to maximize system stability.

One factor which must be investigated in the control system is that of translation between an operators hand or arm motion and that of the manipulator. A disparity between these motions is inherent in the system design. For example, the hand controller not only translates the operator's motion commands to the manipulator, but also acts as a tactile and proprioceptive display to the operator. The physical requirements of the display limit the operator's range of motion. This limitation in hand closure, for instance, must be accounted for in the command structure to the manipulator.

Translation Subsystem.

The example cited above regarding control translation from somewhat limited operator movement to full manipulator motion is just one of a class of issues which we have designated as requiring a translation subsystem. The environment for which the manipulator is designed cannot be displayed directly to the operator. Similarly the control functions of the operator must be translated to appropriate patterns for manipulator kinematics. The translation is conceived to take place in an environment which is intermediate between the hostile or remote environment and the actual operator control area.

The translations must take into account:

- attenuating or filtering hostile environment influences,
- scaling sensory input to an appropriate range for the operator,
- making some modality transformations, e.g., if the manipulator is exposed to damaging influences, the information might be reasonably transmitted to the the operator as a moderately uncomfortable heat sensation which the operator could choose to eliminate if there were need to continue to operate in that environment.
- scaling the operator input to a range appropriate to the manipulator kinematics.
- compensating for system induced distortions in control or feedback, e.g., overcoming the display/control distortion in the hand controller, or compensating for system

inertial properties in the exoskeleton operator/interface.

The intermediate environment concept provides a mapping technique in which translation rules can be imposed in the feedforward and feedback loops of the manipulator system. The imposition of these translations creates an intermediate environment for man/machine interaction.

CONCLUSION

We propose the concept of an advanced manipulator system in which the operator is intimately linked to the system in a state of "remoted presence" as an alternative to current trends in teleoperator research. Examination of the required elements of a telepresent system has generated research issues which must be addressed before the prototype of such a manipulative device can be constructed:

- The necessary density of sensor arrays must be investigated.
- Given use in hostile environments, sheilding of sensor arrays without unduly limiting sensitivity or manipulative ability must be developed.
- The capability of currently available tactile stimulation technology to provide simulation of touch, and the necessity of doing so, must be evaluated.
- Applicability of such physiological phenomena as sensory saltation and inhibition to enhance tactile display capability must be assessed.
- The algorithmic requirements of translating control and sensor information between the task and intermediate environments must be determined.
- The functional environment, in which the operator is to be made to feel present, is referred to as the intermediate environment. The information content of that intermediate environment required for

optimal operator performance must be defined.

- The mechanical subsystem must be made capable of the fine manipulations that high resolution sensor and display subsystems will support.
- The complexity of the control system that integrates the sensor, display,control subsystems, and translation algorithm must be examined to determine overall system stability.

The development of a telepresent manipulator system will contribute to performance in remote manipulation tasks approaching that of a truly present human operator. By immersing the operator so completely in this man-machine system, a remote system may for the first time possess the adaptability of the human being in unexplored environments and unstructured situations. If properly implemented, the master-slave configuration of the system may substantially reduce the computational requirements of the control loop over those of a supervisory control system. Since a remote presence is resultant of the combination of displays of several sensory modalities (visual , auditory, tactile, and kinesthetic) and effector capability, it may provide an avenue for the study of human cognition and perception. In the most advanced state, the sensor/display systems of a telepresent manipulator could allow selective control over the stimuli presented to an operator. Directing research toward the development of such a system may result in both enhanced capability in remote manipulation tasks, and a powerful tool for the study of human psychomotor control.

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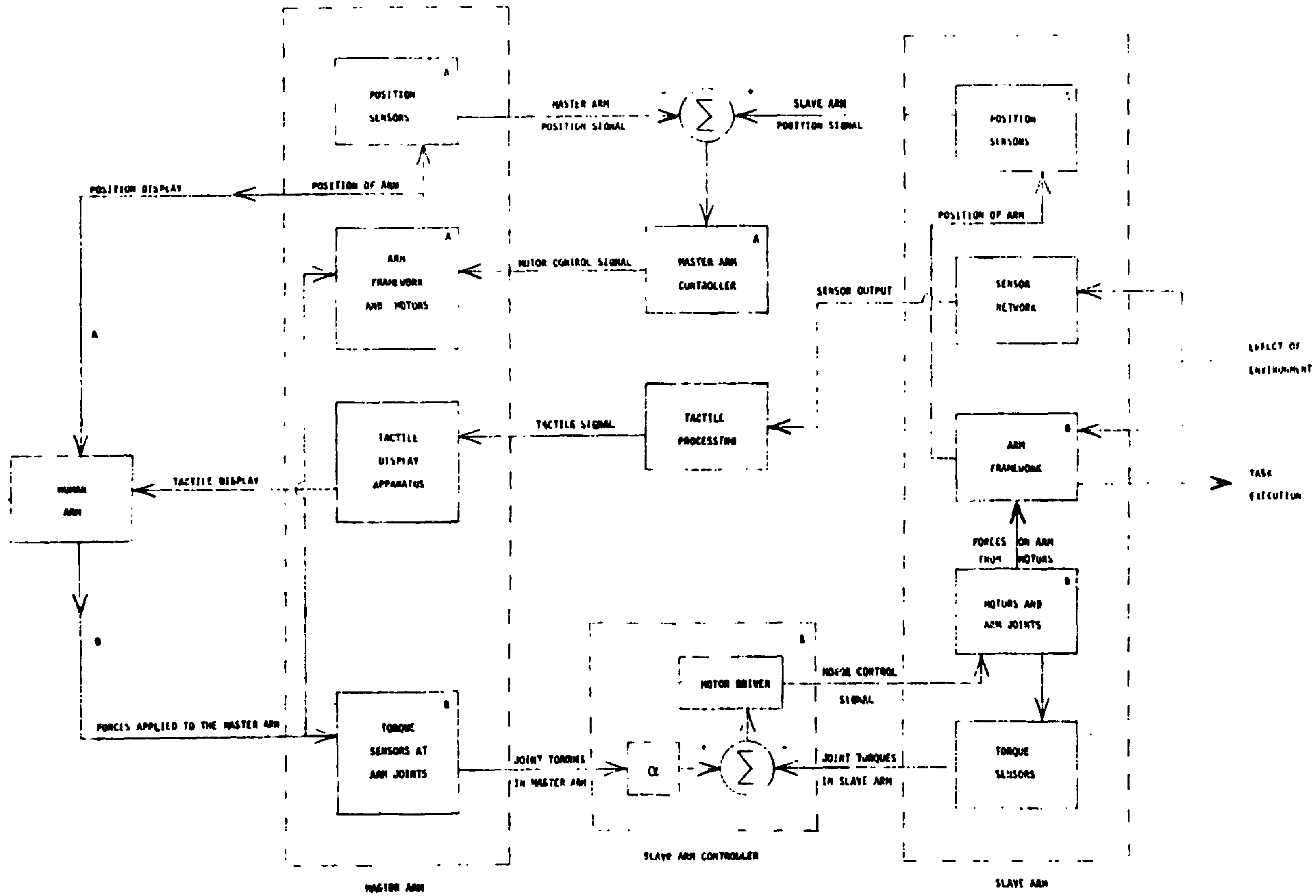


FIGURE 1 TELEPRESENT MASTER/SLAVE MANIPULATOR

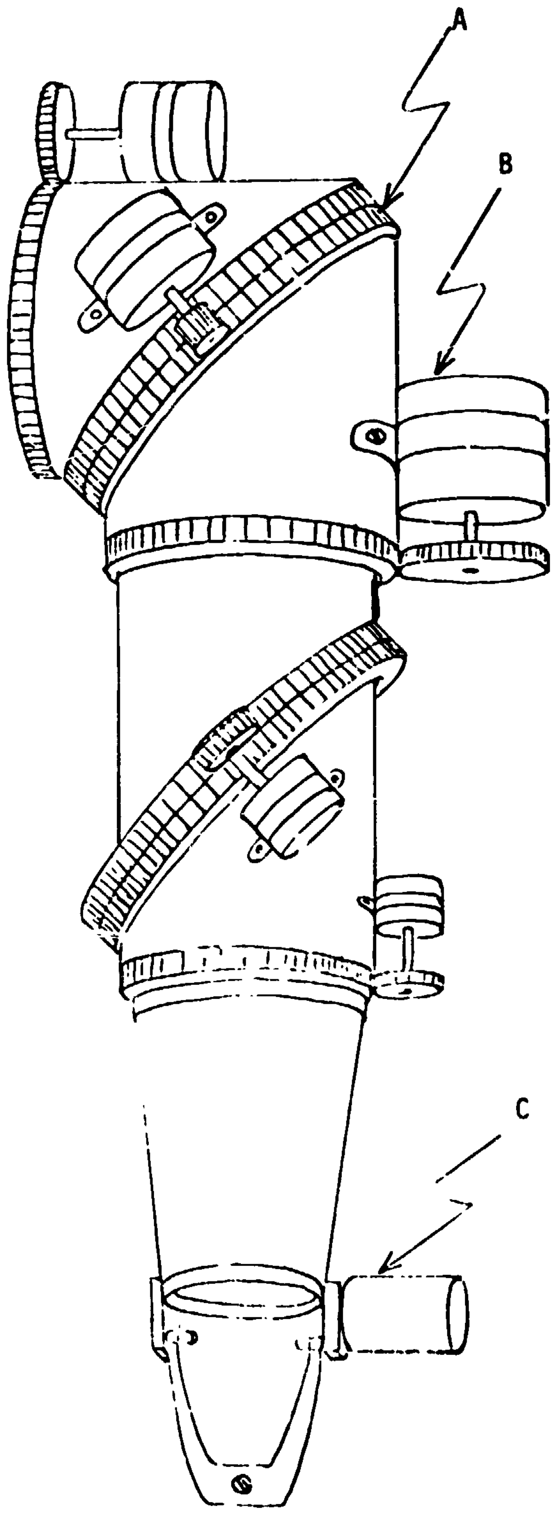


FIGURE 2 MASTER ARM

A) MASTER ARM TORSIONAL JOINT LINKAGE CONTAINING ROTARY POTENTIOMETER

B) SERVO MOTOR PROVIDING POSITION FEEDBACK

C) WRIST FLEXION-EXTENSION CONTROLLER

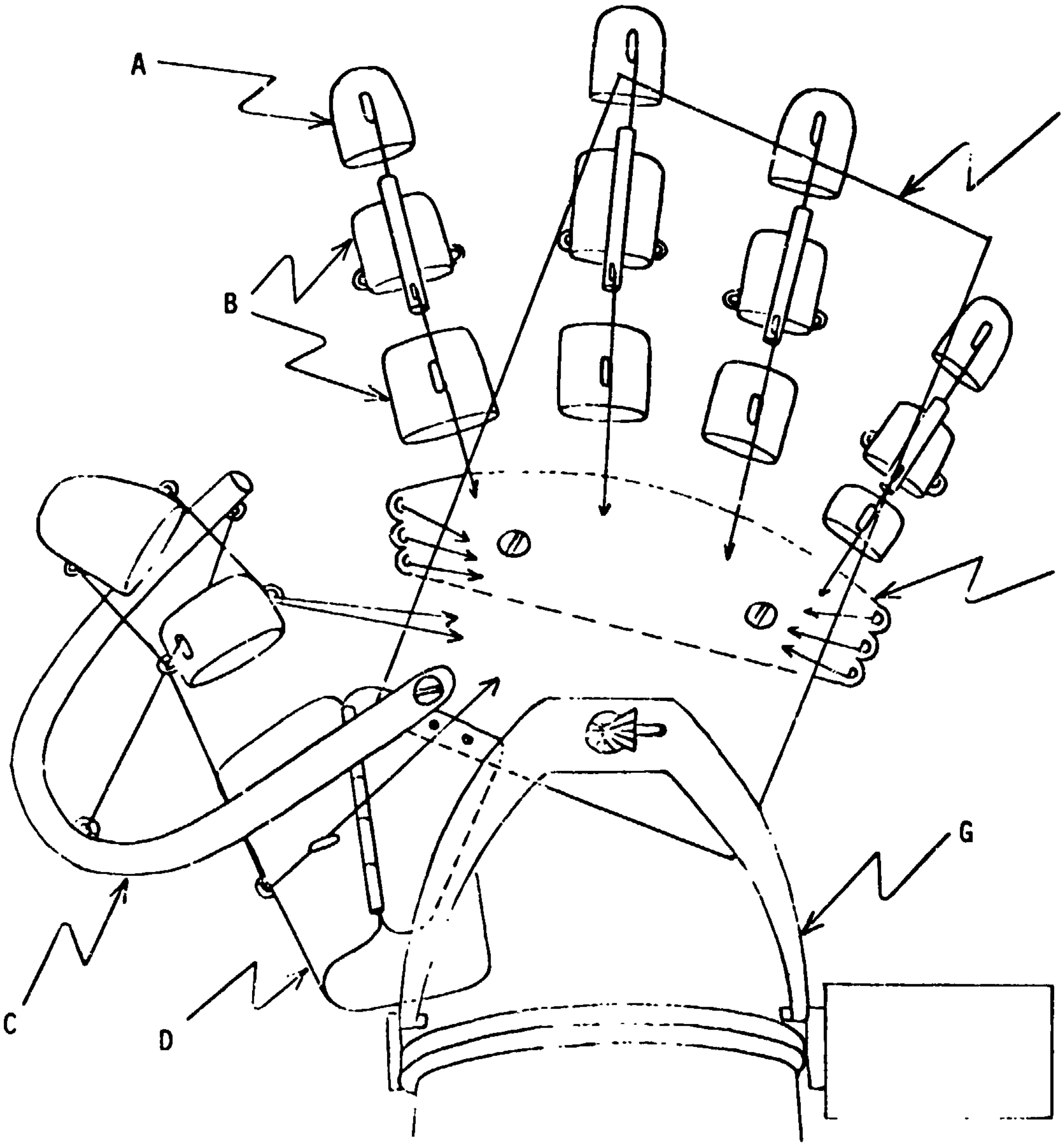


FIGURE 3a MULTIARTICULATED MASTER HAND (TOP VIEW)

A) FINGER THIMBLE AND ELECTROTACTILE DISPLAY

B) FINGER DISTROL RING

C) THUMB DISTROL OUTRIGGER TUBE

D) HINGED LOWER THUMB DISTROL

E) TORQUE MOTOR MOUNTING PLATE (MOTORS NOT SHOWN FOR CLARITY)

F) KNUCKLE BRACE

G) WRIST FLEXION-EXTENSION DISTROL

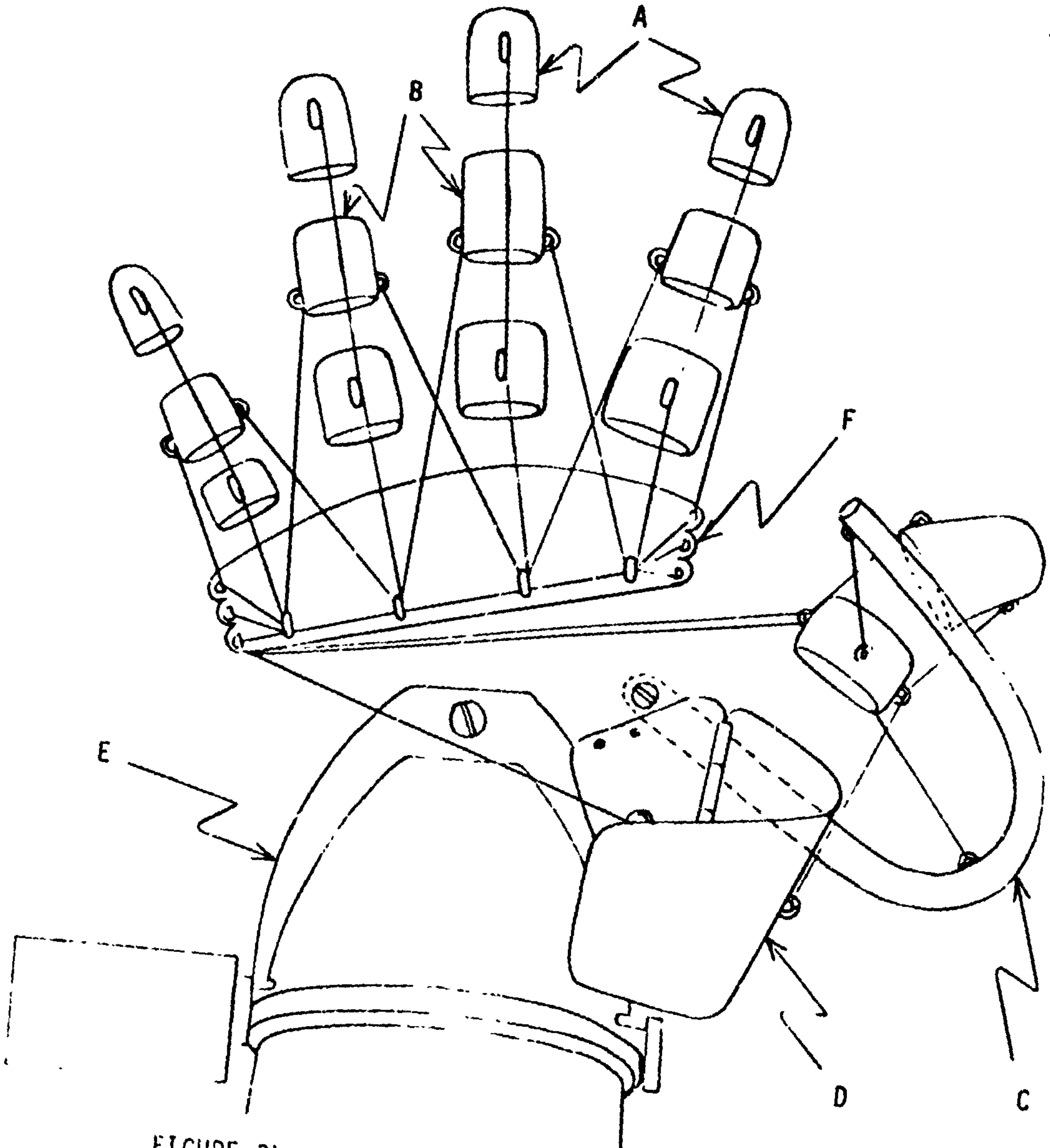


FIGURE 3b MASTER HAND CONTROLLER (BOTTOM VIEW)

A) FINGER THIMBLE DISTROL WITH ELECTROTACTILE DISPLAY
B) FINGER DISTROL RING
C) THUMB DISTROL OUTRIGGER TUBE
D) HINGED LOWER THUMB DISTROL
E) WRIST FLEXION-EXTENSION DISTROL
F) KNUCKLE BRACE

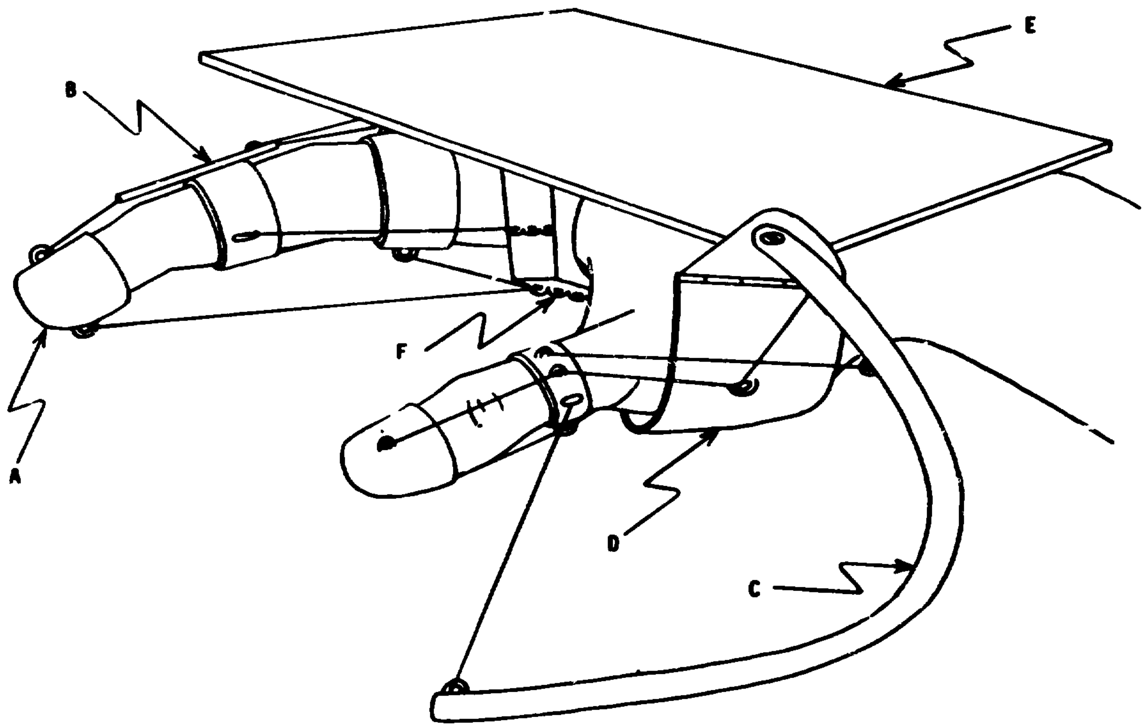
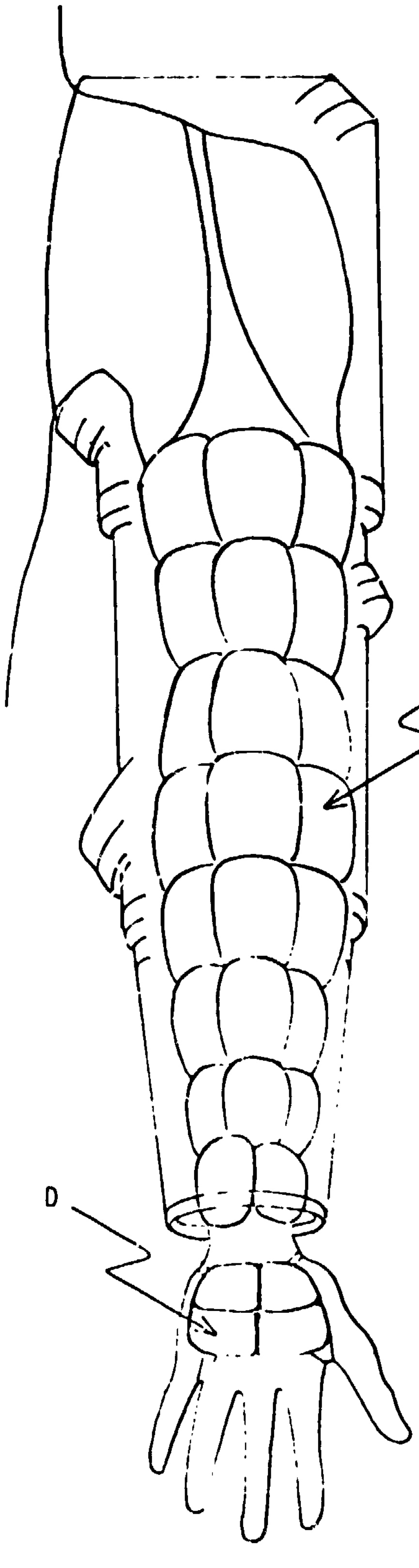


FIGURE 3c MASTER HAND CONTROLLER (SIDE VIEW)

A) FINGER THIMBLE DISTROL WITH ELECTROTACTILE DISPLAY
B) FINGER DISTROL RING WITH CABLE GUIDE
C) THUMB DISTROL OUTRIGGER TUBE
D) HINGED LOWER THUMB DISTROL
E) TORQUE MOTOR MOUNTING PLATE (MOTORS AND CABLE POSITIONS NOT SHOWN)
F) KNUCKLE BRACE WITH EYELETS AND CABLE GUIDES



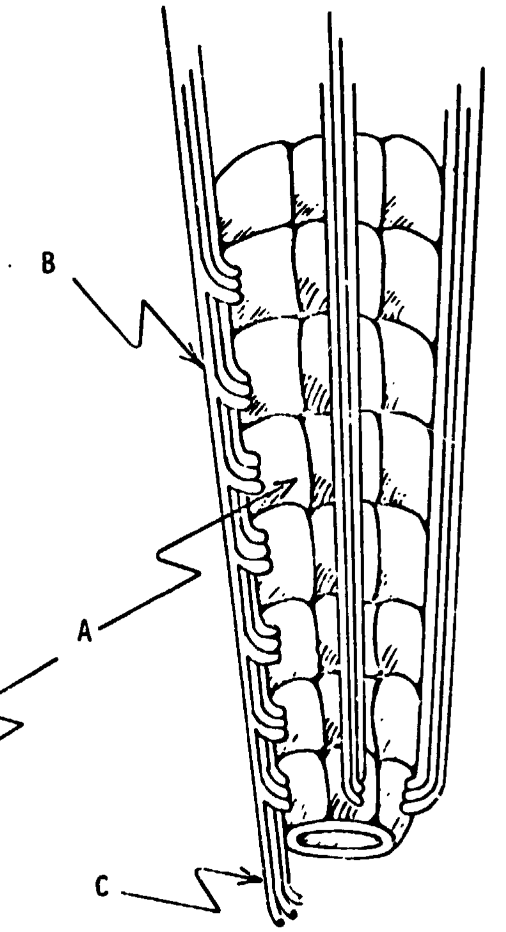


FIGURE 4 MASTER ARM HEAT/PRESSURE DISPLAY

A) INTEGRATED HEAT/PRESSURE DISPLAY POCKET

B) HYDRAULIC TUBING
- HIGH TEMPERATURE FLUID SUPPLY
- LOW TEMPERATURE FLUID SUPPLY
- EXHAUST TUBING

C) TUBES SUPPLYING PALM DISPLAY

D) PALM DISPLAY PAD