OPERATOR-MACHINE RELATIONSHIPS IN THE MANIPULATOR

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INTRODUCTION

Today, the greatest need in manipulator development is for basic systematic information on the factors which influence operator performance. The design of any particular device involves essentially trade-offs between (a) task requirements, (b) equipment performance, and (c) operator-machine effectiveness. When we understand what provisions need to be made to enable the operator to perform specified tasks satisfactorily, then equipment with the intrinsic qualities needed can be built to meet these specifications.

The state of the art in manipulators has progressed sufficiently to make many manipulator types available. The various kinds of remote-handling jobs and the various kinds of robots developed for these tasks provide experience that makes the choice of manipulator characteristics and designs less difficult than in the past. However, the extrapolation of experience gained to be used for the choice of robot design to do more difficult jobs not yet tried is still a tough problem.

To use past experience in robots, many interdependent factors must be considered: operating characteristics needed, combination of motions needed to perform certain maneuvers, combinations of motions needed to perform these same maneuvers and provide adequate force interpretation to the operator, kind of hardware needed to perform the required tasks, and, one of the last considerations, expected machine performance and operator-machine correspondence. Evaluation of the relative worth of these various factors is very important.

The General Engineering Laboratory, a service department of the General Electric Company, has developed manipulators ranging in design complexity from a simple, through-the-wall, three-motion device to the recently developed "Handyman" bilateral hydro-electric servo manipulator. They were developed for particular needs of our own operating departments. Experience gained can be helpful in evaluating operator-machine effectiveness. Because of the unusual combination of characteristics involved in Handyman, the man-machine relationships are quite pertinent.

HANDYMAN

Handyman is a manipulator for special applications that necessitated the development of an electro-hydraulic servo-mechanism of advanced

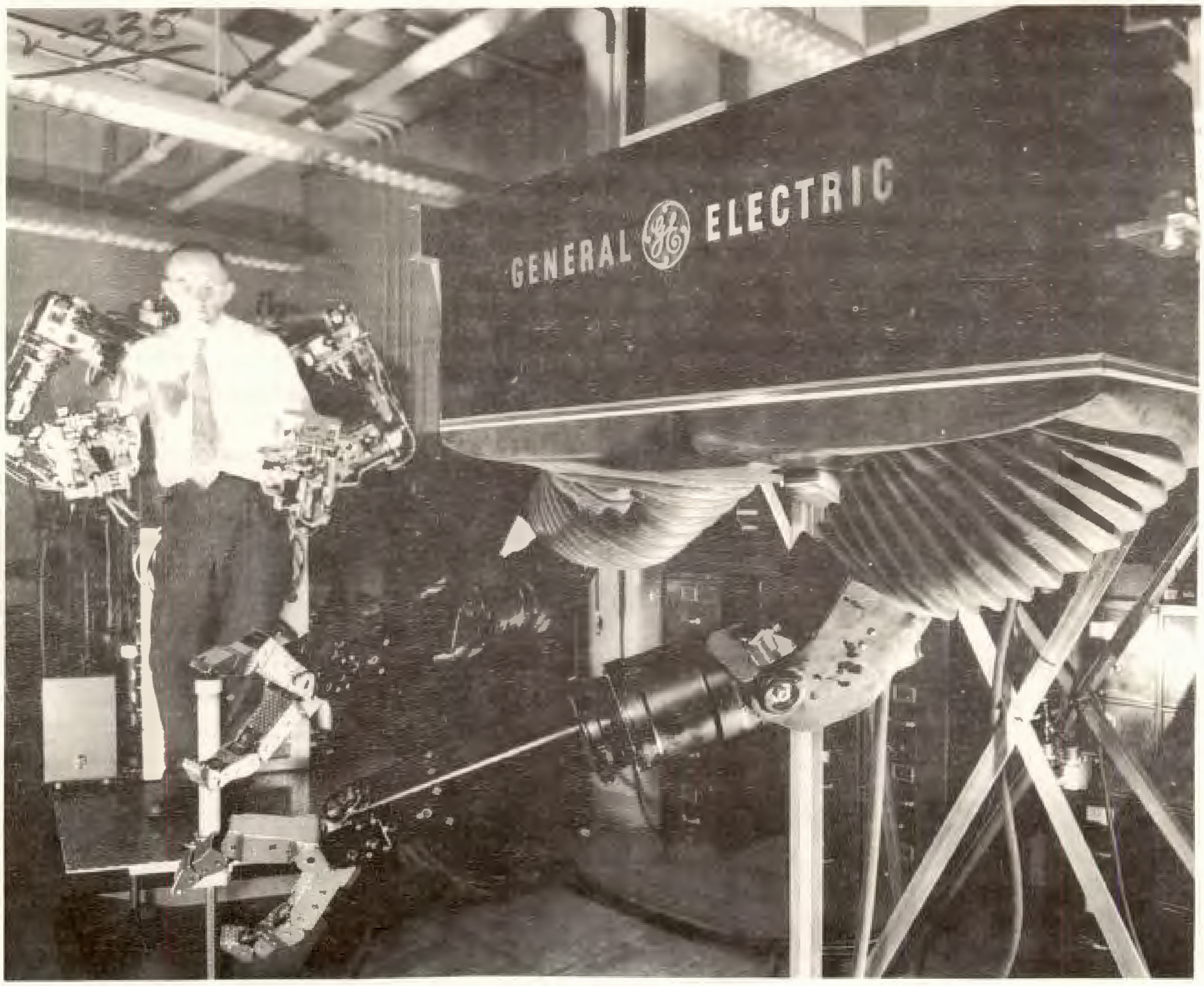


Figure 1. Handyman - Master-Slave Manipulator

design (see figures 1-4). In addition to providing a kinesthetic sense for the guidance of the operator, the system had to satisfy unusually stringent requirements of dexterity, strength, stability, speed of response, and compactness. Finally, the degree of remoteness required made it necessary for the master and slave units to be connected only by electric wiring. The result was a bilateral system, providing continuous spatial and kinesthetic correspondence between operator and slave manipulator.

Relative values of qualitative characteristics can be better understood by considering first-hand experiences, such as gained by operation of Handyman. Even with experience, it is difficult to attribute successful performance to one quality more than to others. But on the other hand, it is easy to pinpoint single weaknesses that hinder operator effectiveness. For the purpose of discussion on relative merits of Handyman characteristics, the following qualities of robots are listed:

1. Dexterity

   (a) Hand motions - hook, clamp, curling fingers, number of fingers, etc.

   (b) Arm motions - rectilinear, telescope or pivot action, number of motions

   (c) Number of arms - one or two

2. Man-Machine Motion Relationship

   (a) On-off switch motion to rectilinear and telescoping motion

   (b) Spatial correspondence - deviations, kinematic to bio-mechanic conformity

3. Force Feedback

   (a) Proportion of force feedback

   (b) Force sensitivity

   (c) Force levels to operator

   (d) Kinesthetic forces

   (e) Tactile sense

   (f) Drift on bias forces

   (g) Friction threshold

   (h) Nonlinearity and saturation

   (i) Required kinematics for force signal integrity

Figure 2. Master Station - Front View

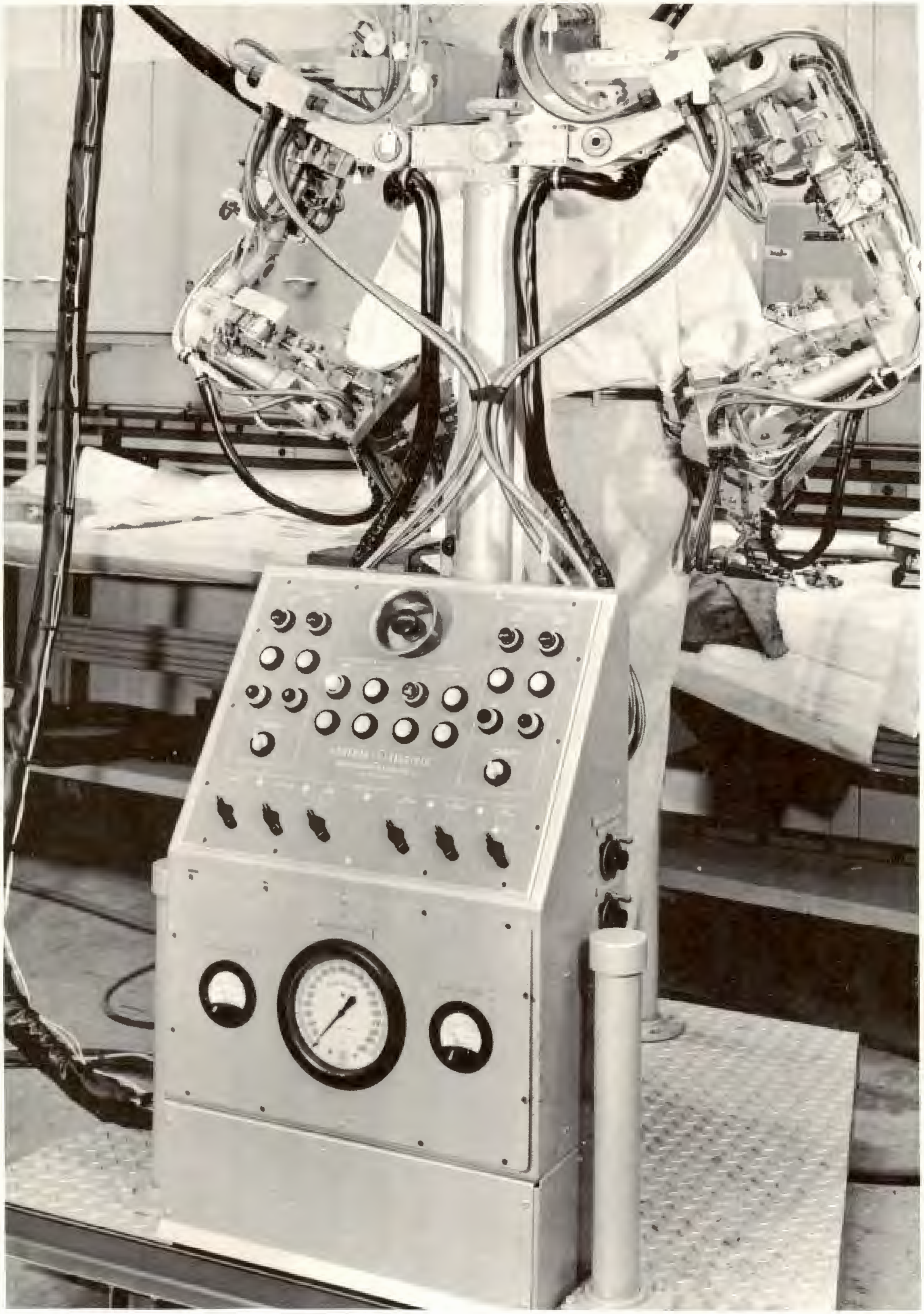


Figure 3. Control Console

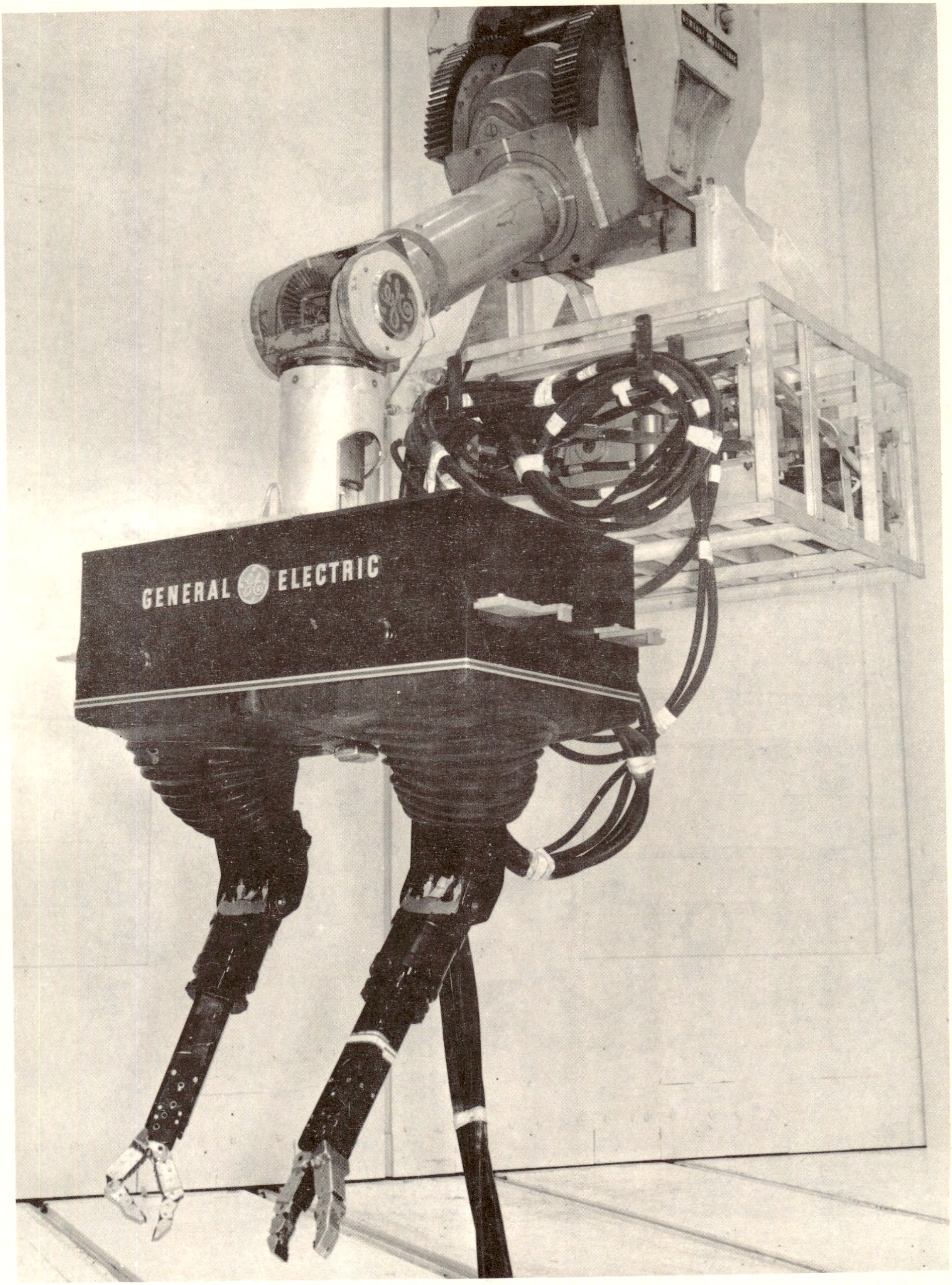


Figure 4. Slave Station Held by ''0'' Man in Hot Shop

4. Dynamics

   (a) Force capacity - proportional "muscle" strength

   (b) Speed of response

   (c) Positioning accuracy

   (d) Response to sudden load change, i.e., grip or load slip

   (e) Start-up and shut-down response

5. Configuration

   (a) Slenderness

   (b) Reach

   (c) Arm link proportions

   (d) Distance between arms

   (e) Hand and finger size

6. Vision and Aids

   (a) Direct-through window

   (b) Binoculars

   (c) 3D TV

   (d) 2D TV

   (e) Audio assist

7. Orientation

   (a) Master to slave

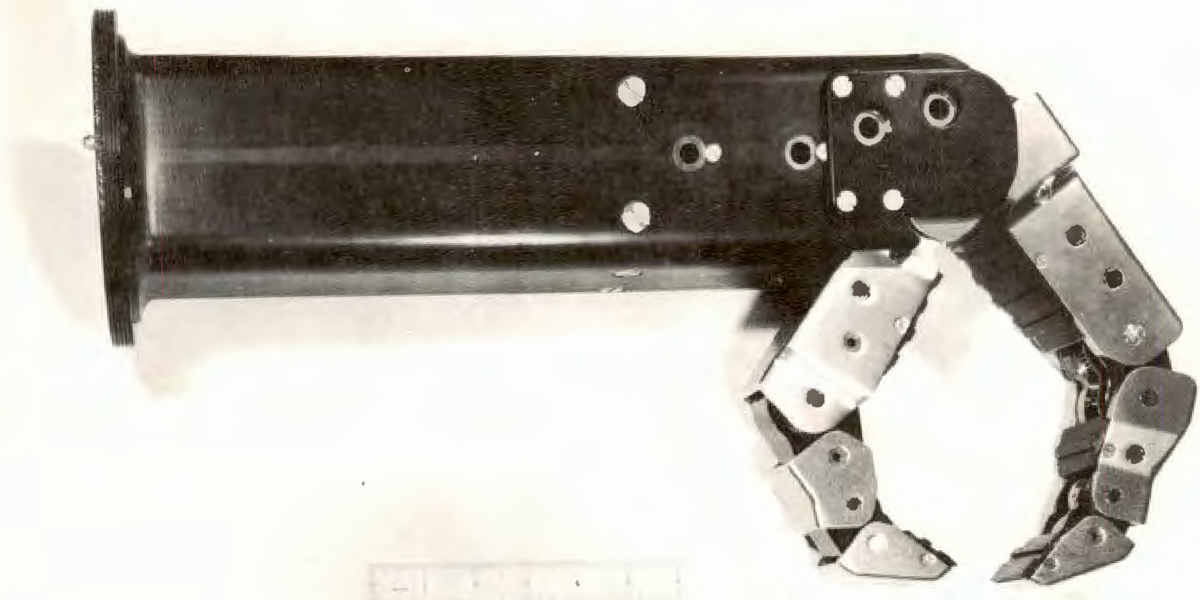
   (b) Mirror image motions

   (c) Viewing aids

DISCUSSION

Handyman has been operated in a huge cell, 160 ft. long, 50 ft. wide, and 60 ft. high. Viewing was through windows and TV. Viewing distance varied from 20 to 100 ft. Obstacles forced unnatural orientation of the slave unit. There was a wide variety of manipulator tasks to be performed. With this kind of experience, consider operator-machine apprehensions with respect to the above list of qualities.

a. Closed



b. Open

Figure 5. Slave Hand

Dexterity

Hand-manipulating ability is most important. To perform very simple grip actions that must be held an appreciable time, the single clamp action is very effective. To do the same job with a multi-motion hand requires operating all motions. To grip and twist things such as hydraulic and electrical disconnects, the multi-action hand is more effective, compared to the single-action hand. This indicates that simple operations are performed more effectively with a simple hand; but a complex operation is performed more effectively with an appropriate multi-motion hand (figure 5).

An adequate number of motions in an arm provides superior ability to maneuver around and in between obstacles. This dexterity saves the time that would be required to relocate the manipulator system or the work or both.

Two arms are advantageous for complex tasks that involve holding and transporting at the same time, pairs of separating or joining forces, or any operation that requires two simultaneous motions. Handyman with its two arms can work with or without force reflection. Two arms without force reflection are poor. In most cases, the advantage of two arms with no force reflection is more than offset by the confusion and hazards caused by uncontrolled internal forces generated. For an operator to hold, with both slave arms, a long, heavy object, he prefers the reaction weight because it gives him force information and, hence, reliability and confidence.

Man-Machine Motion Relationships

Spatial correspondence compared to rectilinear motion is faster because the operator can more easily move more motions simultaneously. Also, the operator is maneuvering in a natural way, thus keeping his mind free of unfamiliar problems.

Figures 6 and 7 show the degree of master-slave kinematic correspondence.

(a) In most all motions, there is a gain of amplitude from master to slave, ranging from 5/4 to 10/4.

(b) There is an increase in slave arm length compared to master.

(c) Master-slave shoulder forward axes are not in parallel planes.

Amplitude gains help compensate for limited amplitude of singular human arm motion. Man's dexterity minimizes this limitation, where machine does not. Exaggerated motions of slave compared to the human operator are an attempt to compensate for the limited dexterity of the machine.

Increase in slave arm size proportions helps in the same way as amplitude gains.

Disoriented master-slave axes allow the operator "living space" between master arms and still he is able to maneuver the slave arms together as a man is capable of.

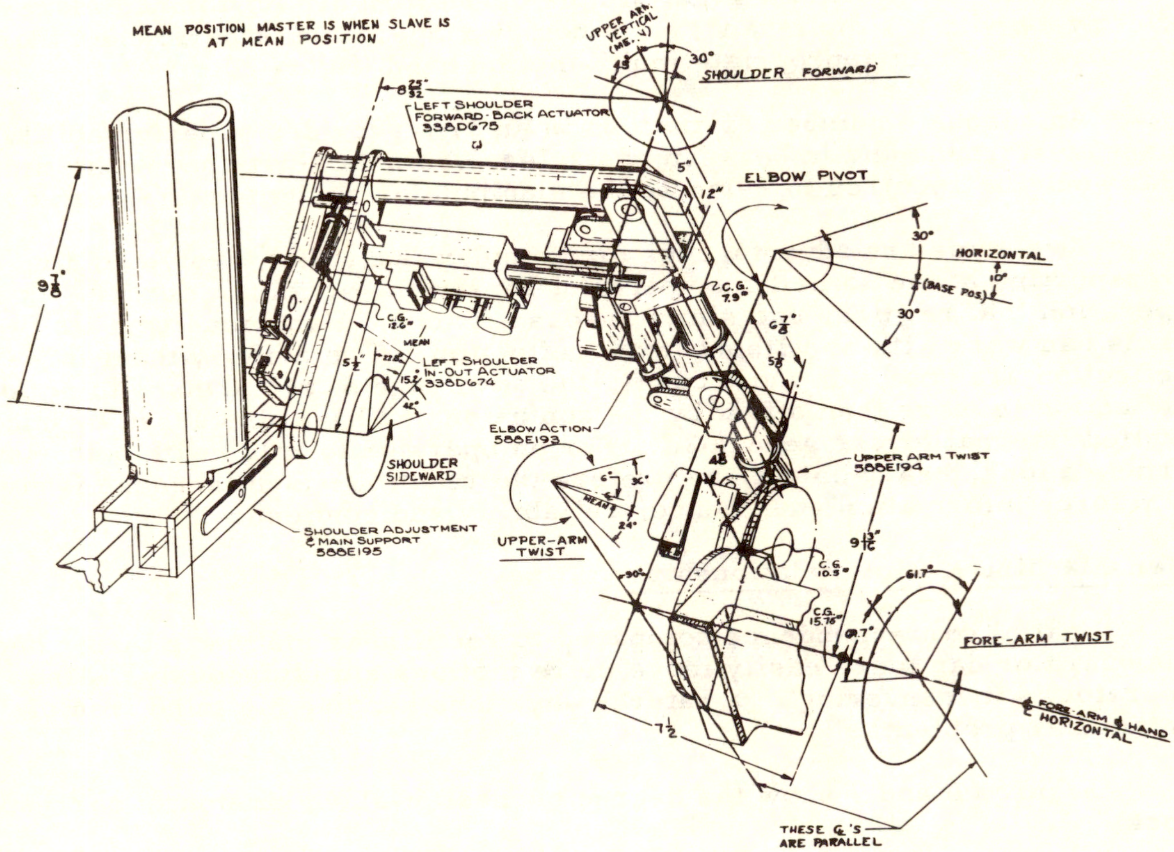


Figure 6. Master Station Kinematics

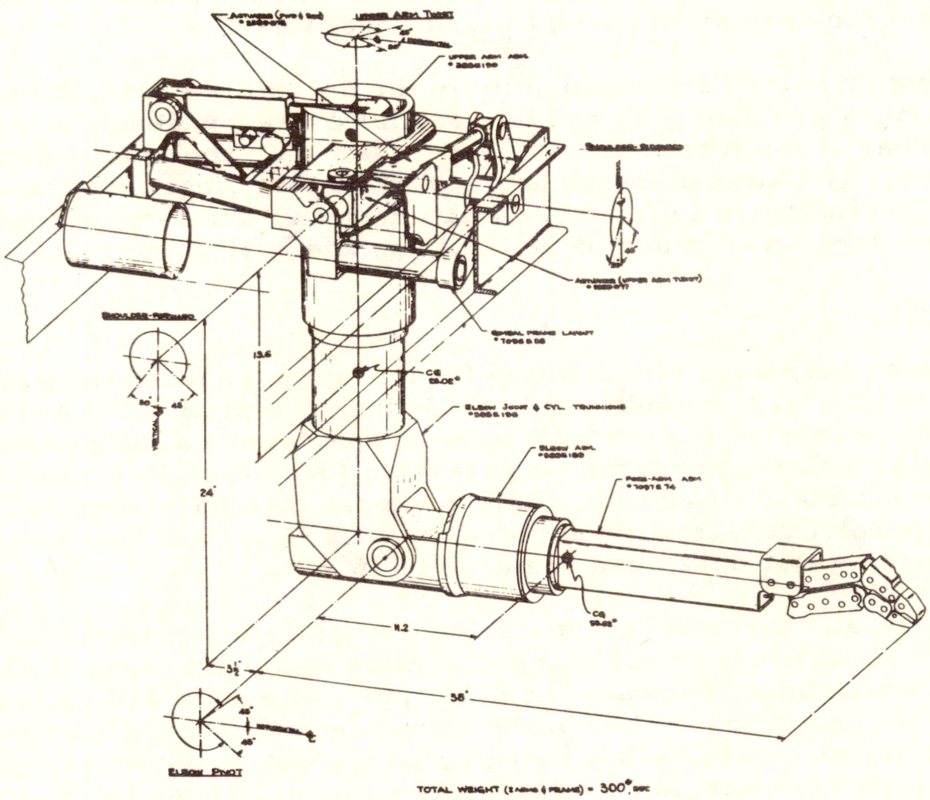


Figure 7. Slave Station Kinematics

With the limited excursions and deviations in spatial correspondence, operator confusion was not caused, except in one case. The advantage of slave range of motions was great. (One pair of slave hands could be separated 9 ft. apart.) The only troublesome deviation was the forearm twist. With a maximum deviation of 90 degrees at each end of the stroke, the operator easily confused one finger with the other. We tried painting the fingers different colors (the thumb green, of course), but that did not help. The failure of color coding shows the strong habit of natural locomotion in a normal frame reference. The other deviations do not bother the operator. It seems that rough correspondence and accurate incremental movements or positioning accuracy are an important pair of qualities.

To provide master hand conformity to the operator's hand, biomechanics is a tricky problem. To provide spatial correspondence in the hand area, the number of motions is limited because of the problem of connection to the operator. The attachment technique for the four finger motions and one wrist motion indicated in figure 2 is satisfactory, but certainly suggests a trade-off problem between number of motions and spatial correspondence.

Force Feedback

There are many ways of indicating force: meter indicators, pre-set force limit levels, visual compliance, audio signal, reproduction of force generated to be presented to operator, and surface tensions in the same way. Handyman reflects the encountered or generated force back to the operator. Tactile forces are not reproduced. Slave hand can pick up 75 pounds. Master can, by selection, reflect to the operator 1/3, 1/5, 1/10, or none of the slave force. Our operators prefer the 1/3 ratio.

The kinesthetic force reflection method requires adequate compound arm motions. An example is pushing on the edge of a door, near the latch. The direction of the push is toward the hinge pin. The door will not swing, and torque is not generated. The "push" cannot be reflected by means of torque measurement. Also, a boy swinging on the door will not have his weight on the door measurable by torque on the hinge. These two examples show cases where force is not reflected because of the mechanics involved. Thus, ambiguities in kinesthetic force interpretations can be expected and depend on the mechanics involved. A horizontal force on the slave forearm (see figure 7) cannot be defined, except as occurring somewhere between the elbow and the wrist.

This discussion will make clear a very interesting point. It is possible to get the slave fingers tangled or caught in machinery being worked on. This is true, even with the assistance of kinesthetic force interpretation to the operator. To avoid this entanglement and possible damage to the hand (from wedging or prying) the operator must depend on good viewing. Adequate tactile clues would do also, but this is a severe design problem. Too many fingers or not enough are both problems of limitations in performance.

Force drift is a serious hindrance to operator proficiency. When there is no load at the slave, the force at the master must be zero. Any erroneous bias allowed to persist would rapidly tire the operator and create confusion in force interpretations. Manual adjustment was provided to buck out force bias in Handyman. This was not good enough; automatic compensation had to be provided.

Friction level in Handyman is low enough that it does not bother the operator. However, the friction is enough to prevent threading a needle, but not to prevent position and lift operations such as those expected in a shop or lab operation.

Force feedback provides the abilities to work two arms in unison, guide slender tubular pieces into holes, scribe a circle dictated by the crank or wheel being turned, and follow a compound curved surface. On the other hand, there are disadvantages, such as: (a) complexities in design and adjustments and (b) holding a hand force or grip soon tires the operator's hand.

The slave machine is protected from damage by overload or collisions because of the force reflection feature. Therefore, the operator can approach a task with greater confidence and speed.

Dynamics

The force required to do a job depends on the efficiency of the kinematics and force reflection. Consider the swinging door as an example again. Assume it works hard. Man will very deftly maneuver himself in order to push in a direction parallel to the floor and normal to the door force. If the manipulator were required to do this job and could not manage to push in this ideal direction, the manipulator efficiency would be very poor. Dexterity, viewing, and force reflection would help in this example. Notice that without force reflection the manipulator could be pushing down with high force, just because of mismatch of two non-conforming motions.

Handyman is capable of average speeds required in laboratory work. If the speed were limited further, the operator would feel this hindrance.

Force reflection, combined with speed limitation, prevents quick reaction to sudden change in loads. The reaction does not bother the operator and it protects the slave equipment. These factors also protect the machine from sudden and dangerous motions during start-up and shut-down. This is one of the reasons for not reducing force reflection to zero. At zero, the slave manipulator can be easily damaged.

Configuration

Figure 8 is drawn in proportion, showing the degree of slenderness, shape, and size. The similarity to man's arm proportions is effective, and seems to make operator manipulating very natural. Of course, one arm instead of two would take less space and be more maneuverable in tight spots. However, the long arm reach of Handyman has kept this hindrance factor to a minimum.

Hand size has proven to be good; however, it has difficulty holding small diameter rods normal to the forearm axis.

Vision

Because of poor resolution of 3D TV compared to 2D TV, the latter was preferred. Further, binoculars (for long distance) were used in preference to 2D TV because of better resolution or acuity of sight. Audio assist to hear clicks of contact and scraping of sliding parts helps.

Orientation

Many cases of disorientation are not hindrances to remote handling; on the contrary, they sometimes help. One of the worst cases that helped, rather than hindered, is TV viewing with receiver and transmitter 180° opposed to each other and both 90° in viewing direction away from operator line of sight. The operator could see his task directly through a window. The transmitter was looking at the task 90° to the left and the receiver was viewed 90° to the right of the operator.

Another unusual condition is the case of mirror action: slave looking at the master. Both master and slave correspond in direction of north-south and oppose in east-west directions. This arrangement provides excellent viewing and no confusion to the operator.

Other viewing aids that help in tight spots are mirrors and bright lights for sharp shadows.

SUMMARY

The number of potential applications for remote manipulators is large. Each application will involve design compromises. It is none too early to develop the kind of data and concepts that will guide these compromises so as to permit effective and efficient operation performance.

Reference

R. S. Mosher, "Force-Reflecting Electro-Hydraulic Servo-Manipulator," Electro-Technology, page 138, December 1960.