DESIGN AND EVALUATION OF A BACKHOE MODEL WITH A MASTER-SLAVE CONTROL

by 6408

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CHAPTER I

INTRODUCTION

Remote handling, as a part of the material handling field, has received noticeable attention in the last two decades because of the problems arising from working in environments and/or using materials which are deleterious to health. More than 80% of manipulator arms built in the period from 1948 to 1967 were shipped to atomic energy installations where the environment is hazardous.

Rate control is the predominant mode of control in many manipulators, in some prototype artificial arms, and in most industrial equipment. Another common control method in various manipulators is master-slave control in which the operator moves a set of control arms which are similar to the arms of the manipulator. The remote slave duplicates the motion of the master providing a position rather than rate control, thus making the manipulation more natural. This method of control involves the Cybernetic Anthropomorphous Machine (CAM) principles. A CAM, as defined by Mosher [1]*, is the type of system often used in tasks requiring human qualities like judgement, continuous sensory appraisal, force and position sensing, etc.

As mentioned before, attention has been concentrated in the area of materials handling where the environment or the materials are hazardous. Up to the present time, advanced manipulator principles have not been applied in routine materials handling equipment. In these applications rate control is still the dominant mode of control.

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*Numbers in brackets refer to references in bibliography.

The purpose of this thesis is to demonstrate, by using a backhoe model, the feasibility and desirability of applying modern manipulator control concepts to routine materials handling problems. It is anticipated that such a control will enable an operator to learn quickly, to reach a higher level of skill, and possibly to reduce abuse of equipment.

In most industrial equipment, the operator has several levers or switches, each controlling an actuator for a given degree of freedom. To move an object from one location to another the fastest and most efficient path is along a smooth continuous curve obtained by moving the hand between these locations. To accomplish this with the conventional control system, the operator must actuate several controls simultaneously. It is unlikely that the operator will be able to specify speeds and directions for more than two degrees of freedom simultaneously. Therefore he must approximate the desired path by a series of piecewise straight line sections. This is time consuming, and demanding of operator skill and equipment response. What is desired is a more natural, integrated type of control which allows the operator to effectively control all degrees of freedom simultaneously. In a resolved motion system, for example, Whitney [2], the motions of the various actuators are combined and resolved into separately controllable hand motions along world coordinates such as horizontal, vertical, reach along the hand direction, and so on. Thus an operator is enabled to call for the desired hand motion directly along axes relevant to the task environment. This is the type of control system to be considered in this thesis.

Description of the Conventional Backhoe

This article is written to familiarize the reader with the main components and operation of the conventional backhoe.

The conventional backhoe has four degrees of freedom corresponding to four actuators. Each actuator is controlled through a rate control system, i.e., the speed of each actuator at each joint is proportional to the displacement of the corresponding control handle. These handles are connected mechanically to spool valves. Thus the operator has four separate levers which he must use to control the motion of the bucket. Plate I shows a photographic view of the main parts of a backhoe.

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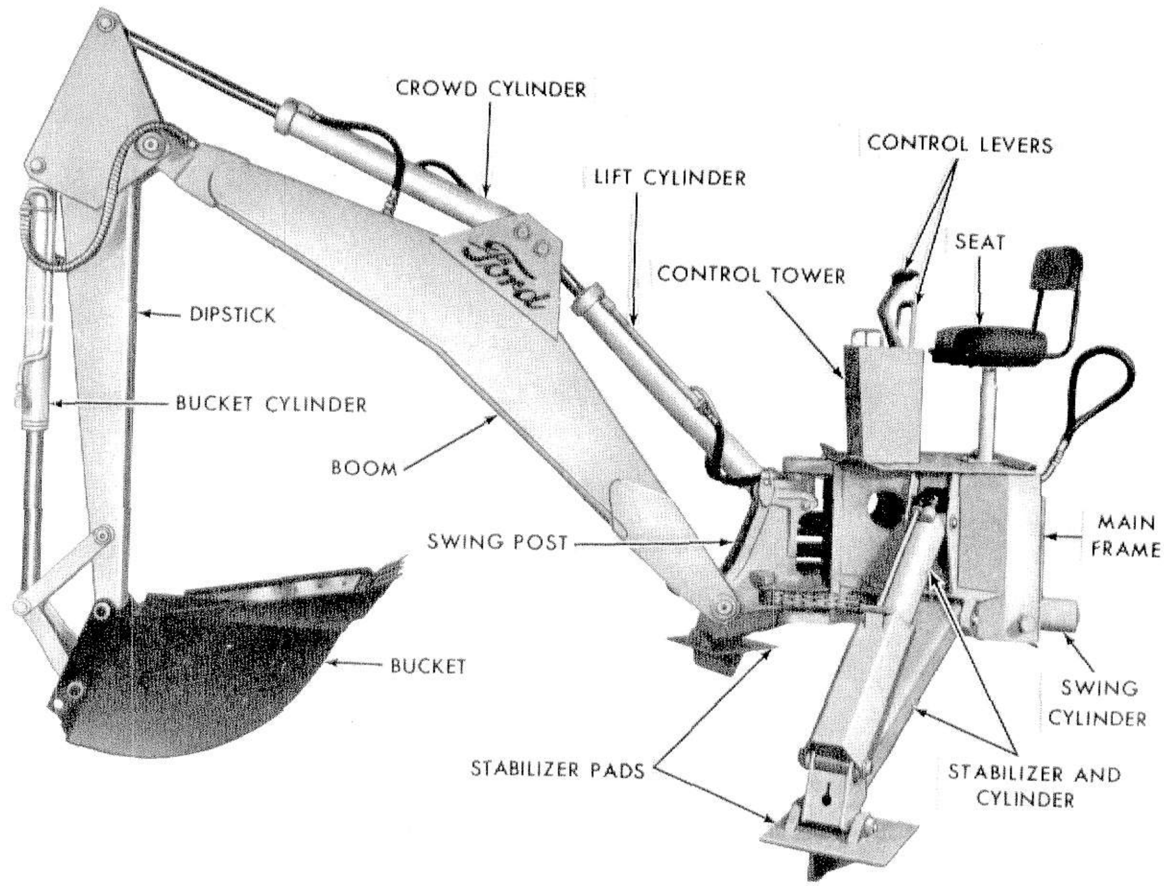
EXPLANATION OF PLATE I

Photographic view showing the main components of a conventional backhoe. The main arms considered are the boom, dipstick, and the bucket. (Courtesy of Ford Motor Company)

PLATE I


CROWD CYLINDER
CONTROL LEVERS
LIFT CYLINDER
SEAT
CONTROL TOWER
DIPSTICK
BUCKET CYLINDER
BOOM
MAIN FRAME
SWING POST
BUCKET
SWING CYLINDER
STABILIZER PADS
STABILIZER AND CYLINDER

CHAPTER II

LITERATURE SURVEY

A manipulator is a machine used for remote handling. A manipulator operator uses one or more control mechanisms to position the remote arm and to provide the grasping motion necessary for remote handling of materials. The primary application for remote manipulators has been in handling hazardous materials such as in hot labs and atomic energy installations.

The development of manipulators has taken place primarily in the last two decades, with emphasis on hazardous environments and materials. The technology developed in solving these problems has not been widely applied in more routine industrial tasks such as earth moving and freight handling. Application of manipulator technology to these new fields is suggested by the similarity in structure and tasks of manipulators and some types of industrial equipment. This thesis will show the validity of this concept through use of a scale model of a backhoe. As a basis for the backhoe design and evaluation, a short summary of pertinent manipulator literature is presented.

The development of manipulators began in 1947 at Argonne National Laboratory (ANL) with mechanically connected manipulators and electrically connected unilateral manipulators considered first, [3]. For the present purposes, manipulators may be classified as mechanical, electric, electrohydraulic, and hydraulic. This survey will cover the development of these kinds of manipulators.

MECHANICAL MANIPULATORS

In 1948, Goertz [4], and [5], and his coworkers at ANL developed the Model-1 bilateral mechanical master-slave manipulator. This master-slave manipulator has seven degrees of freedom. They are X, Y and Z motions, twist, azimuth and elevation rotations, and the grip degree of freedom. The three wrist degrees of freedom and the grip degree of freedom are communicated by means of cables. Cable paths are short and friction is low enough so that forces are reflected. The machine is bilateral in fact as well as in principle, so the operator can feel what is going on in the various degrees of freedom. The Model-1 (M-1) master-slave manipulator does not have the elbow joint and is limited to a load rating of only about one pound. The biggest problem with the ANL M1 was that it was restricted to hot cells without ceilings because of the movable over-the-wall support tube.

This master-slave manipulator turned out to be successful, and the operator very quickly learned to manipulate a variety of solid objects within its reach and load capacity. It was learned at this time that the operator soon (usually, in less than an hour) directed most of his attention, not to what he was doing with his own hands as they manipulated the master handle, but rather to the motion of the slave tongs and the object being manipulated.

Goertz [4], developed Model 3 and Model 4 Manipulators. Model 3 Manipulator was the first master-slave manipulator to be put into regular operation in a hot cell. Model 4 was built shortly thereafter. It had quite low inertia and low friction. Because of these factors, many operators preferred it to some of the later models. The slave arm entered the shielded enclosure through a hole in the roof and, consequently, there were radiation shine problems.

In 1950-51, Goertz [4], developed the Model 6 Manipulator. It was designed to work through a hole in the wall instead of through the roof. This manipulator was commercially produced and used in quite a number of facilities, but was made completely obsolete when the Model 8 Manipulator went into production.

In 1953, Goertz [4], developed the Model 7 Manipulator. It is similar in overall performance to the Model 4 except that the wrist joint, tongs, and other arrangements are designed so that the slave arm can work inside a boot. The manipulator was produced where moderately light loads are encountered such as in chemistry work.

In 1954, Goertz [4], [5], and [6], developed the ANL Model M8, or Mod 8, as it is often called. It became the standard hot-cell manipulator in the 1950's and it still is. Commercial concerns, such as Central Research Laboratories and AMF Atomics, have manufactured thousands of manipulators built around the basic ANL Mod-8 configuration.

In the Mod 8, a fixed horizontal tube supports both master and slave arms which are pivoted at either end of the tube. The tube can rotate but not slide back and forth. Up-and-down motion along the length of the arms is accomplished by tape-controlled telescope action on the slave end, a distinctly nonanthropomorphic movement. The four degrees of freedom associated with the hand are also communicated through metal tapes or cables running over a system of pulleys. Model 8 like model 1 is bilateral in seven dimensions.

The Model 8 master-slave manipulator is improved over the Models 4 and 6 manipulators in the following aspects: ease of installation, simple indexing, large area coverage, low friction, stronger wrist joints, remotely detachable tongs, capability of being booted and modest cost.

The Model 8 has its weak points: cable stretch, wrist-joint gears fail, and there is some cross coupling between different degrees of freedom. These problems have been overcome to some extent by commercial manufacturers.

Despite the great advances inherent in Mod 8, an operator can only work about one-sixth as fast with it as he can with his bare hands.

The standard Model 8 Manipulator has load capacities of up to 25 pounds. One special version of this manipulator is rated at 100-pound load capacity.

Mechanical master-slave manipulators are doing a good job within their load capacities and volume covered. It is believed that they will continue to be a very useful tool for handling radioactive materials and for a few other applications.

ELECTRIC MANIPULATORS

Electric manipulators are either unilateral or bilateral manipulators [3].

Unilateral Electric Manipulators

The arms in this kind of manipulator consists of a series of joints and links, with each joint driven by an electric motor. The operator usually actuates these joints with either an array of switches or a joystick without force feedback of any kind.

The Los Alamos Minotaur [5], and [7], is an electrical unilateral manipulator. It was built by General Mills, Inc. for maintenance of a reactor at Los Alamos Scientific Laboratory. It has a pair of manipulator arms plus a second pair of adjustable arms holding lights and TV cameras which protrude from a sphere-like turret supported from above by a bridge-crane carriage.

The PaR Model 3000 manipulator [5], and [8], developed by Programmed and Remote Systems Corp., consists of hand, wrist, forearm, elbow, upperarm, and shoulder. Each of the upper and lower arm segments is one foot long. All of the motions are driven by DC motors, and each is powered by a separate magnetic-amplifier system to provide stepless variable speed control.

The main deficiency in such rate controlled manipulators to date has been guiding operation where specified paths are to be followed.

A recent development at Programmed and Remote Systems Corp. [8], is an auxiliary control system for rate controlled manipulator, whereby the motions of the manipulator follow the motions of the operator's hand and arm. The controller is mounted on a pedestal which is adjustable in height. The pedestal supports a kinematic replica of the manipulator, so the operator's arm motion corresponds more closely with those of the manipulator arm, making control more anthropomorphic. The auxiliary controller can be used interchangeably with the standard rate controller. A switch on the hand, is used to switch between the two.

Rate controlled manipulators generally are used where the loads to be handled and the forces and torques to be applied are greater than a person's capacity. Because the forces are not reflected to the operator through the controls, the operation is not tiring.

Bilateral Electric Manipulators

About the same time work was being done on the mechanical master-slave manipulators in the late 1940's, work was also in progress on developing servos which have the "output follow the input", and also have the input load proportional to the output load.

In 1954, Goertz, [3], [4], and [9], built an electric master-slave manipulator incorporating servos and force reflection. The master-slave position control of the manipulator arms and hands plus force reflection made this the first bilateral electric manipulator (Model E1). This was used experimentally to determine the behavior of force-reflecting servos relative to their capabilities of producing adequate force reflection. The force reflection of the manipulator was reasonably good. This manipulator has seven suitable independent motions. Manipulator load capacity is about 4 pounds. Maximum lineal velocity was 24 inches per second.

Goertz [4], developed the Model E2 electric master-slave manipulator which is stronger and more reliable pair of manipulators than Model E1. These manipulators were mounted on both wheeled vehicles and overhead supports for tests. They have a load capacity of about 8 pounds in any direction.

Model E3 was also developed by Goertz [4], at Argonne National Laboratory. It has a slave arm capability of exerting 50 pounds in any direction on an intermittent basis and 30 pounds continuously. The maximum force that can be exerted on the masterhandle is about 17 pounds. The slave can have either the same or three times the force of that reflected to the master.

In 1964, work was being done by Goertz [4], on an improved electric Master-Slave Manipulator ANL Mark E4, having a load capacity of 50 pounds. At that time (1964), Goertz pointed out that the principal improvements of this manipulator over Model E3 are as follows:

1. the manipulator slave arm will be able to reach work from many directions;
2. the master arm will be better suited to working with different types of viewing, such as windows, periscopes, and television monitors;

3. the slave arms will be provided with better cooling so that they can work in higher ambient temperatures;
4. it is designed to allow the slave arms to be operated at a distance of up to 2,000 feet from the master arms.

The Argonne Mark E4A, [10], is one of the latest in a series of electrical master-slaves dating from the early 1950's. The motions and degrees of freedom of the Mark E4A, [5], are essentially the same as those of the Mod-8 mechanical master-slave. Most of the degrees of freedom are driven by tapes like those employed in mechanical master slaves. The difference is that these E4A tapes are actuated by servo drive motors located in the rather substantial "body" of the slave arm.

Electric master-slave manipulators have several advantages over mechanical manipulators. They can be mounted on movable supports so that the slave arm can manipulate through a much larger working volume and approach the work from various directions. In addition, needing only the sealing of an electric cable, the slave arm can work in a controlled atmosphere. Also it should be noted that in outer space and in some nuclear and undersea tasks, it is one of the best engineering solutions to the problem of projecting man's dexterity over distance and through recalcitrant barriers. The major disadvantages are complexity and large cost.

ELECTROHYDRAULIC MANIPULATORS

Unilateral Electrohydraulic Manipulators

The combination of electrical command signals and hydraulic actuation is logical for small submersible manipulators. Sea water has been used as the hydraulic fluid for some devices such as the NEL (Navy Electronics Laboratory) manipulator, [5].

The Beaver submersible, developed by North American Aviation, Inc., [11], has two manipulating arms. It is a general purpose utility craft capable of manipulating objects outside of the protective hull, sheltering the human operator.

The General Electric electrohydraulic unilateral manipulator, [5], has a square or rectangular, rather than circular, cross section of the arms. This was done to ease fabricating the arms and also because of the desire to enclose wires, hydraulic lines, and actuators.

The Westinghouse Model-200 underseas electrohydraulic manipulator, [5], can lift up to 500 pounds and rotate any of its joints at speeds from 0° to 18° per second. The model possesses six degrees of freedom.

Bilateral Electrohydraulic Manipulators

The General Electric handyman built in 1958 by Mosher [1], [5], and [7], like the first Argonne National Laboratory mechanical and electrical master-slaves, represents a milestone in teleoperator technology. Besides being the first electrohydraulic bilateral master-slave, it was also the first to employ articulated exoskeletal master arms that conform to the operator's arms. In this system the operator does not have to support the weight of the harness (which was called the "follower rack", by Mosher), or of the slave, or even of his own arms, because the machine is designed to exactly counter-balance all these masses regardless of the arm position.

Handyman's dexterity results from its total of ten bilateral degrees of freedom per arm-hand combination. These are: shoulder, 2; upperarm twist, 1; elbow, 1; forearm twist, 1; wrist, 1; hand, 4. Each motion is hydraulically actuated by means of electrical signals that cause the arm and hand to carry out precisely the same motions as those made by the operator's finger and arm angular motions. The information associated with the registration of the positions and forces by the machine, when handling an object, is translated to electrical signals and sent back to actuators attached to the operator, which convey to him forces proportional to those experienced by the machine. The Handyman slave arms can lift 75 pounds in their weakest position, i.e., when they are separated the farthest.

HYDRAULIC MANIPULATORS

The Hydroman, built by Oak Ridge National Laboratory, [5], and [12], represents one of the few attempts to construct an all-hydraulic teleoperator. Hydroman was built for through-the-wall hot-cell operations involving heavy loads. It was given an elbow but no up-and-down telescoping action. The forearm delivers 1000 in.-lb. of torque from an internal, reversible hydraulic motor. The wrist joint is a hydraulic cylinder with a rack and gear assembly to convert linear motion into rotary motion. Force reflection or feel is not transmitted back through the power loop, but through a differential feedback cylinder and a feedback ratio bar. Friction, line expansion, air in hydraulic fluid, shift of O-rings in grooves, etc., cause tracking error, i.e., the slave does not follow exactly the master. Correspondence between forces is nonideal too.

In October, 1966, General Electric, [1], and [5], concluded that a powered exoskeleton could be constructed that would enable a man to lift 1500 pounds 6 feet and carry this load 25 feet in 10 seconds. The General Electric Company expected to have it completed for test and evaluation in the spring of 1968. In the GE (General Electric) concept, the operator stands inside an anthropomorphic structure built in two halves that are joined together only at the hips by a transverse member called the "girdle." The exoskeleton parallels the operator everywhere save at the forearm. The force ratio is about 25. Mechanical stops, fail-safe control, and safety crash bars are incorporated.

The skeleton has 15 joints on each side, which enable it to carry out most of the important human motions, save for those requiring considerable dexterity of the hand.

In the GE concept, the operator exerts a force against the closely fitting control surface at any particular degree of freedom. The surface then moves relative to the encasing slave member and, in doing so, actuates a valve in the master control circuit. The signal is transmitted hydraulically, so the GE man amplifier is all-hydraulic, somewhat like the Oak Ridge Hydroman.

From the above literature survey, it is noted that a large body of knowledge and experience has resulted from the development of manipulators. Equally evident, however, is the lack of any application of the technology in other materials handling problems.

CHAPTER III

DESIGN OF THE NEW BACKHOE CONTROL SYSTEM

Because a backhoe is more anthropomorphic than most other industrial equipment, it was chosen as a test item for the application of modern manipulator principles. This chapter is concerned with the design of a master-slave backhoe control system for a small model.

GENERAL CONSIDERATIONS

As a person transfers an object from one location to another, most of the degrees of freedom of his arm and hand are actuated simultaneously, and the hand moves along a smooth continuous path in space, in a natural way. The purpose of the new control system is to let the operator transfer the bucket of the backhoe between locations in space along a curve similar to the smooth continuous curve the operator would follow in moving his hand. Under such control, the bucket of the backhoe can mimic the path of the operator's hand, but on a bigger scale of displacement. The most natural way to achieve this is to develop a master-slave pair, i.e., a master to be manipulated by the operator and a larger slave to follow. With a single control handle, the operator moves the master along any desired path in space and the backhoe arms obediently follow. Thus, it is no longer necessary for the operator to decide which degrees of freedom are to be actuated but only along what path he wishes the bucket to follow. All necessary degrees of freedom will be actuated simultaneously. This is a very natural type of control which should allow the operator to learn quickly and reach a high level of skill.

The first step in designing a model master-slave controlled backhoe is to establish the general character of the master. The slave is more or less fixed by the task definition for a backhoe. It is believed that best control will be achieved when master arms are very similar to the slave arms.

To choose the shape of the master, one must first establish which of the degrees of freedom of the arm-hand combination are essential. The arm and hand may be approximated by a system composed of four levers rotating on four centers through a total of nine degrees of freedom, [13]. Figure 1 indicates these degrees of freedom.

As each joint of the arm undergoes motion, the hand moves along the desired path in space and consequently each joint in the master undergoes a corresponding motion in time. If each counterpart joint in the slave can be made to undergo the same motion as the master, then the backhoe bucket will follow the hand on a proportional displacement basis. Thus, the control problem is one of transferring motion from each master joint to the corresponding slave joint on a one-to-one basis. It is to be noted that for the joints of the backhoe arms to carry out precisely the same motions or motions proportional to those experienced by the corresponding joints of the master, the control system used must provide position control rather than rate control. Position control is an inherent feature of master-slave control whereas rate control is used in controlling conventional backhoes. With these ideas in mind, a suitable shape for the master can be selected. This shape is shown in Fig. 2. The arms of the master are called the upperarm, the forearm, and the handle. To reduce cross coupling between the degrees of freedom of the master, the axes of rotation of the handle and the hand must be as coincident as possible. This requirement is satisfied by the design shown in Fig. 2-b.

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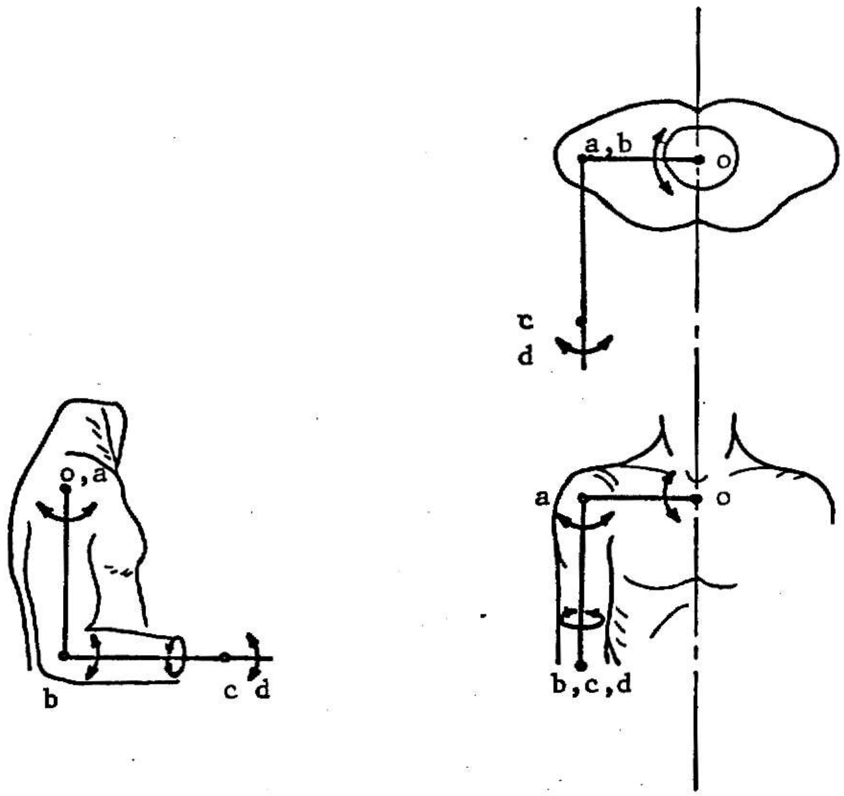


Fig. 1. Approximation of the Arm and Hand.

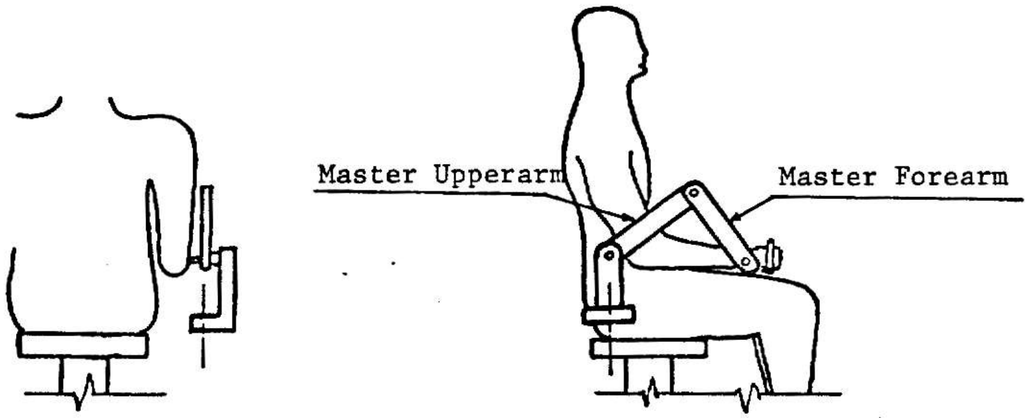


Fig. 2-a. Master Arm Shape for Four-Degree of Freedom Backhoe.

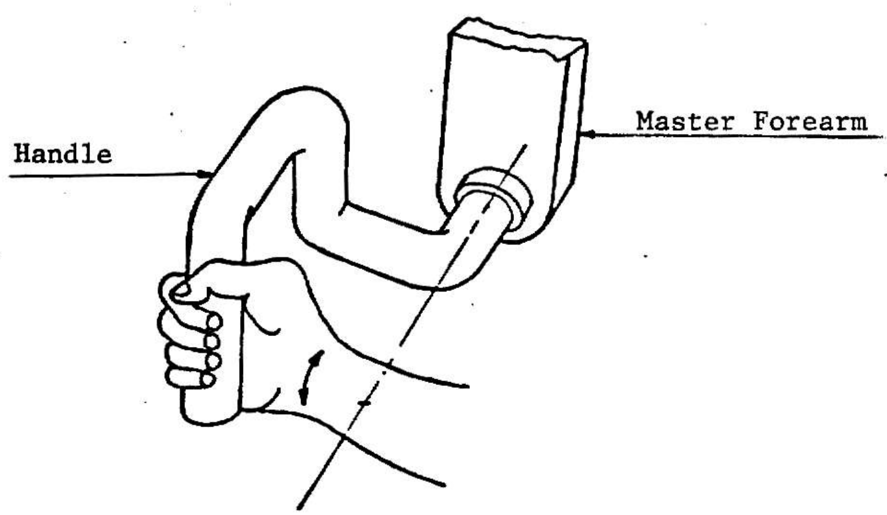


Fig. 2-b. Isometric Illustration for the Handle.

A backhoe, typically, has only four degrees of freedom, all of which are now to be controlled by using only a few of the degrees of freedom of one arm-hand combination. One thus thinks of the possibility of making use of the unused degrees of freedom of the arm-hand combination and the free arm-hand combination to control more than four degrees of freedom. To demonstrate this, a concept of a six-degree of freedom backhoe will be presented next.

Six-Degree of Freedom Backhoe

It is expected, regardless of the type of control inherent in the backhoe, that a backhoe having six degrees of freedom will enable the operator to perform more complex tasks than those performed by a four-degree of freedom one. One possible suitable configuration of such a backhoe is shown in Fig. 3. Six, is the minimum number of degrees of freedom which will enable an operator to dig ditches in the form of either straight lines or curves, in any desired direction rather than only in the plane of the backhoe arms, and to transfer materials between confined places as shown in Fig. 4. By fixing the two additional degrees of freedom, the backhoe becomes a four-degree of freedom one.

For a six-degree of freedom backhoe, the master arm may take the same general shape as that shown in Fig. 2-a, but with the handle replaced by a mechanism such as indicated in Fig. 5-a. To avoid cross coupling between the two wrist degrees of freedom, axes a-a and b-b shown in Fig. 5-a must pass through the corresponding centers of rotation of the wrist. This mechanism is suitable for controlling five degrees of freedom. A simple rate control for bucket rotation around axis c-c shown in Fig. 3 can be provided by a thumb

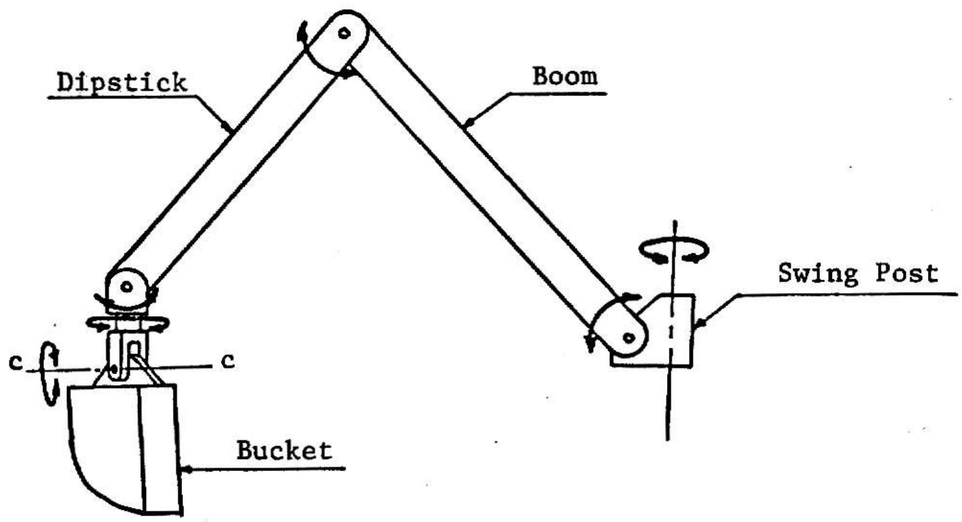


Fig. 3. Six-Degree of Freedom Backhoe.

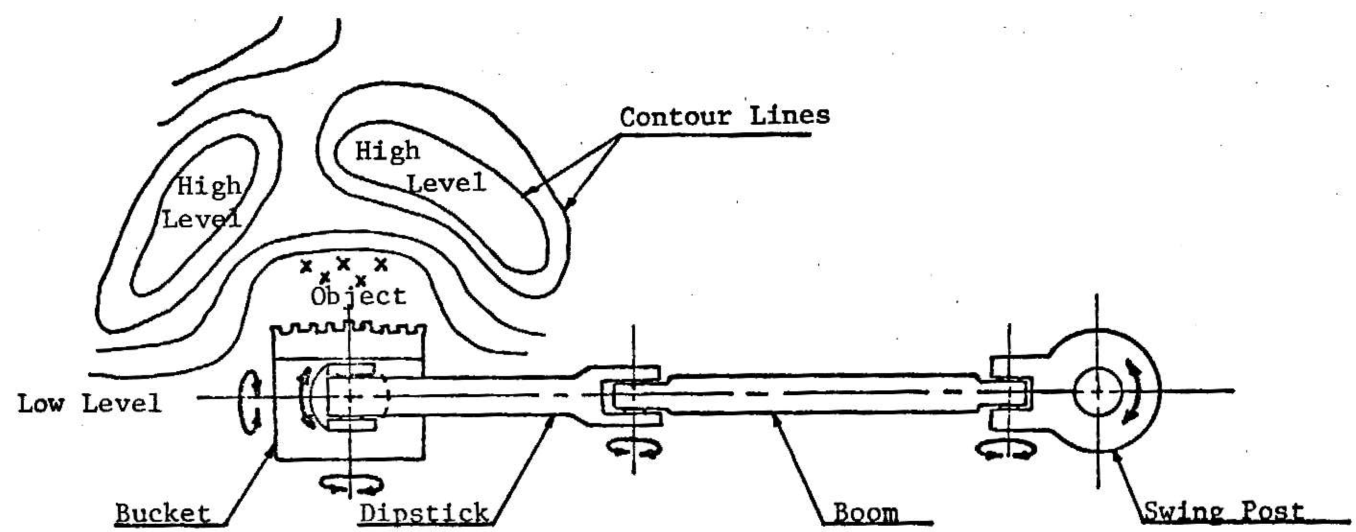


Fig. 4. Plan View for Six-Degree of Freedom Backhoe in Confined Operation.

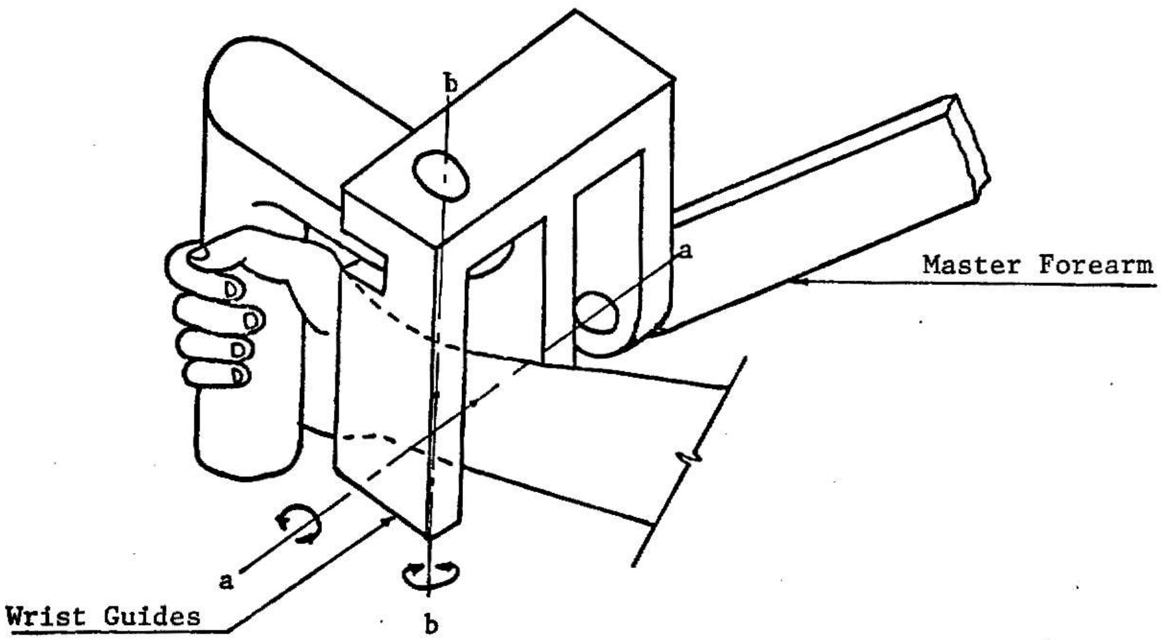


Fig. 5-a. Wrist Mechanism for Six-Degree of Freedom Backhoe.

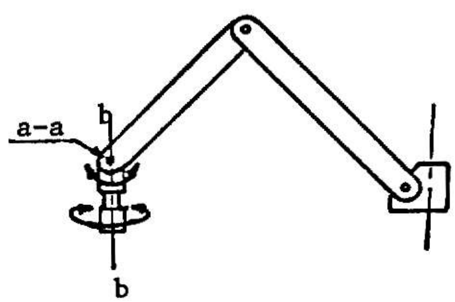


Fig. 5-b. The Two Motions Actuated by Wrist.

button, foot control, or a left hand control. Position control could be provided but the uses for this degree of freedom are such that rate control would probably be adequate.

Figure 5-b combined with Fig. 5-a shows the correspondence between the two wrist degrees of freedom on the master and on the slave.

The rest of this chapter will be devoted to the detailed design of the components and the operation of the model backhoe.

BACKHOE LABORATORY MODEL

The following are the benefits derived from building and testing the model.

1. To test the feasibility of the control concept.
2. To determine the learning response of a group of subjects.
3. To determine operator opinion about this type of control.
4. To provide a model which can be used for comparison with a similar scale model of a conventional backhoe.
5. To generate design information for future use.

Because of the great expense and complexity associated with the building of an externally powered model, a manually powered design was selected. The nature of master-slave control suggests the use of closed hydraulic circuits for positive transmission of forces and motion and to provide force reflection.

The system consists of two main parts, namely, the master arms and the slave arms which mimic the motions of the master arms. As mentioned before, the arms of the master are called the upperarm, the forearm, and the handle. The arms of the slave are called the upperarm, the forearm, and the bucket, which correspond to the upperarm, the forearm, and the handle, for the slave, and correspond to the boom, the dipstick, and the bucket for a conventional backhoe. Since both, the master and the slave, consist of links forming articulated members, they can be easily connected hydraulically. Three of the motions of the master are transmitted hydraulically to the slave by means of three closed hydraulic circuits. The swing motion is transmitted mechanically through pulleys and a belt to the slave. Transmitting the swing mechanically is simple since these motions occur around axes which are stationary and parallel.

To fulfill the function of the model, the following design requirements were specified.

1. All the motions of the master were to be transmitted exactly to the slave causing its arms to carry out precisely the motions experienced by the master.
2. Compliance in the motion transmission system and in the structure must be low to avoid positioning errors, excess load sensitivity, and vibration problems.
3. There must be no leakage in the system so that the register can be maintained.
4. The system was to be bilateral to provide direct force reflection to the operator.
5. The level of the forces acting on the operator's arm and hand was to be low to avoid tiring the operator.
6. Friction force levels were to be kept below operating force levels to provide good operator load sensitivity.
7. The system must be counterbalanced, so the operator does not have to support the weight of the arms.

8. The control must be comfortable for the operator and the operator must have good visibility of system operation.

The main components of the system are the actuators, the arms, the counterbalance, and the hydraulic circuit.

Actuators

Shown in Fig. 6 is a complete drawing of an assembled actuator. Plate 2 is a photograph of a disassembled actuator showing the component parts. These include the cylinder body, the piston rod, two pistons, two bellofram, and two end caps. Shown also in the same plate are two washers, copper tube, and hose connections. A bellofram seal was used to provide a leakage free actuator, to keep friction forces to a minimum, and to avoid the need for close tolerance machining on the pistons and cylinders. The bellofram also serves as an end cap gasket. The bellofram have a little if any axial expansion at the working pressure level and hence contribute little to system compliance. The removable end caps facilitate actuator assembly and bellofram replacement. The piston rod, cylinder, pistons, and end caps are all made of aluminum for light weight construction and resistance to corrosion. Pressure buildup behind the pistons is prevented by air vents in the cylinder body.

Arms

A set of four links are used to form two articulated arms, the master arm and the slave arm. The lengths of the links in the master arm and in the slave arms are shown in Fig. 7. To get kinematic similarity between the master and the slave, the ratio of the lengths of the upperarm and forearm of the slave with respect to the corresponding links at the master was chosen to be about 1.35:1. Also this ratio keeps the level of the reflected forces

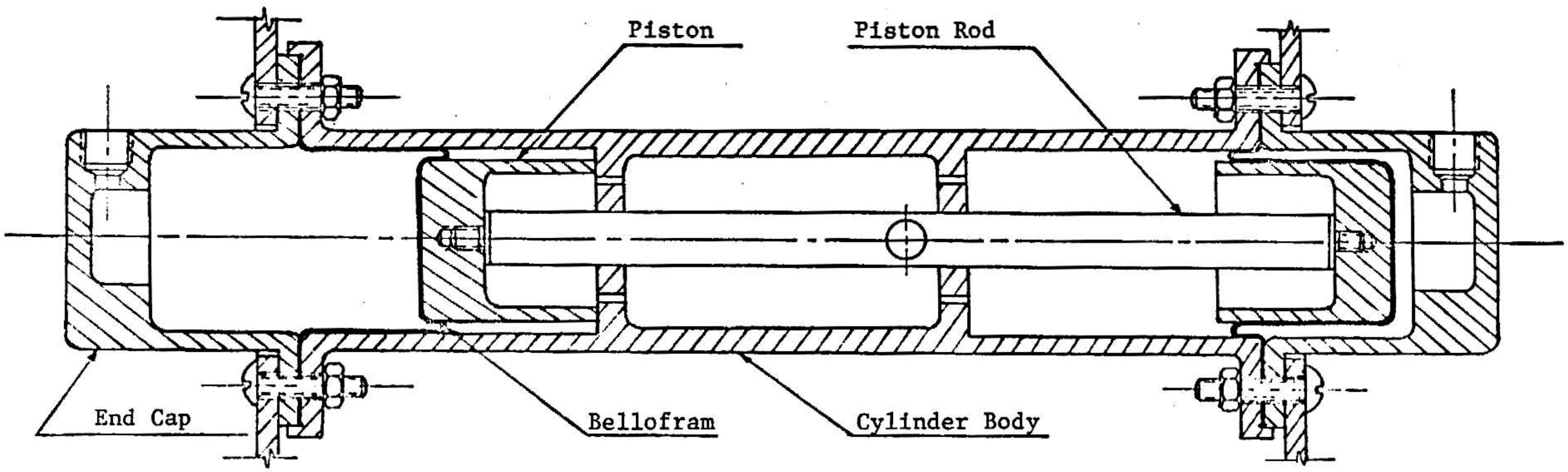


Fig. 6. A Complete Actuator.

EXPLANATION OF PLATE II

Photographic view showing the main components of an actuator.

PLATE II

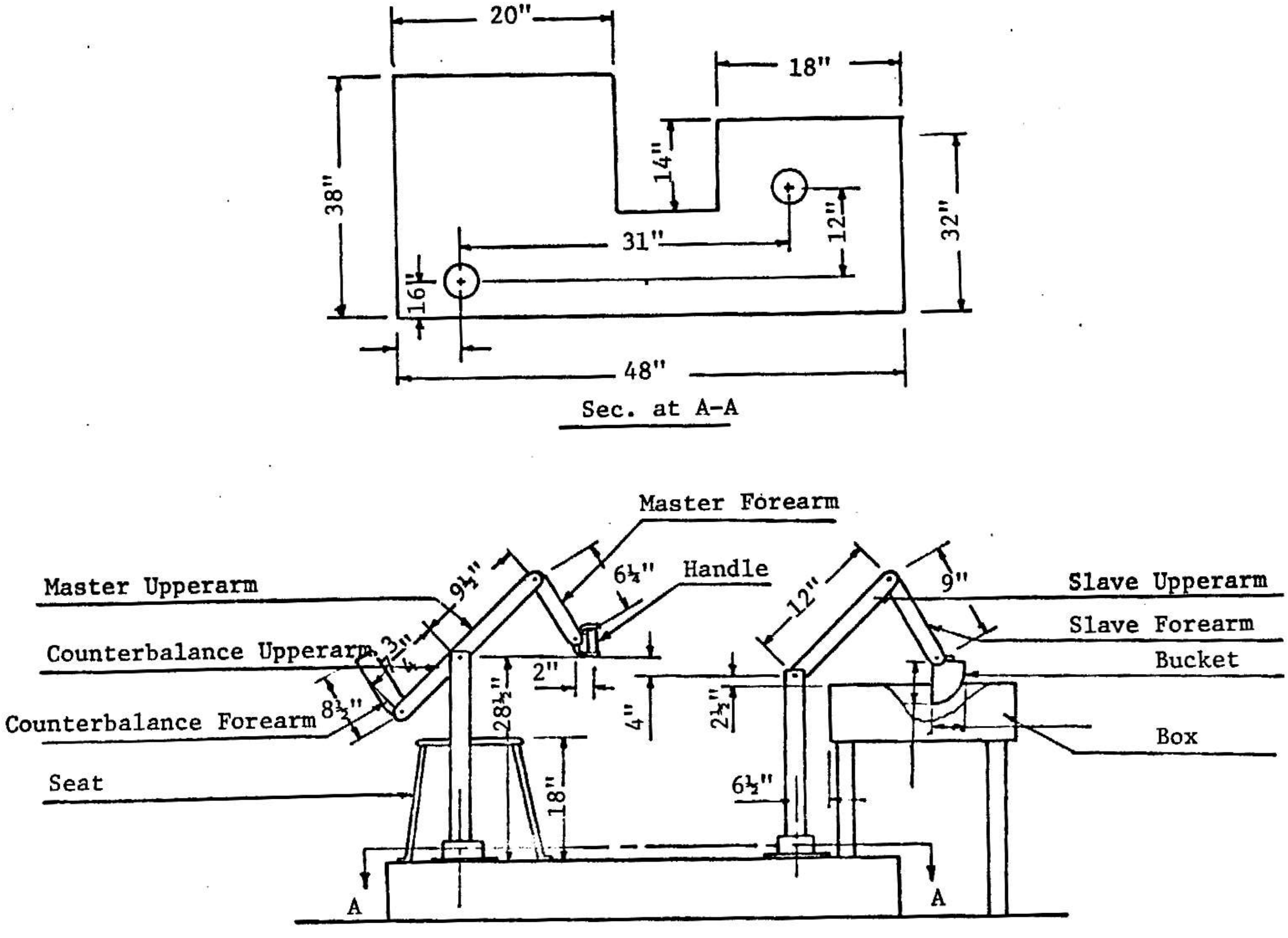


Fig. 7. Main Dimensions of Workstation and Model.

acting on the operators arm and hand low. On an absolute basis, the lengths of the upperarm and the forearm of the slave were chosen to be 12" and 9" to reduce the inertia forces. The length of the master arm was chosen not to exceed the comfortable reach of the operator. The master arm contains a two component composite counterbalance, the detailed design of which will be discussed later. Each of the upperarm and forearm of both, the master and the slave, has as the principle structural element one of the actuators discussed above. Reinforcement is provided by a skeleton composed of the copper tubes used to carry the hydraulic fluid in the control and actuation system. These design features are evident in the photograph of the model shown in plates III and IV. This type of structure results in a strong but light system; a factor of paramount importance in a manually powered model. Plate III indicates the correspondence between the motions of the master arm and the slave arm. Because of the wide range of bucket rotation compared to that of the handle, a linkage similar to that used in a conventional backhoe is necessary to rotate the bucket.

Counterbalance mechanism

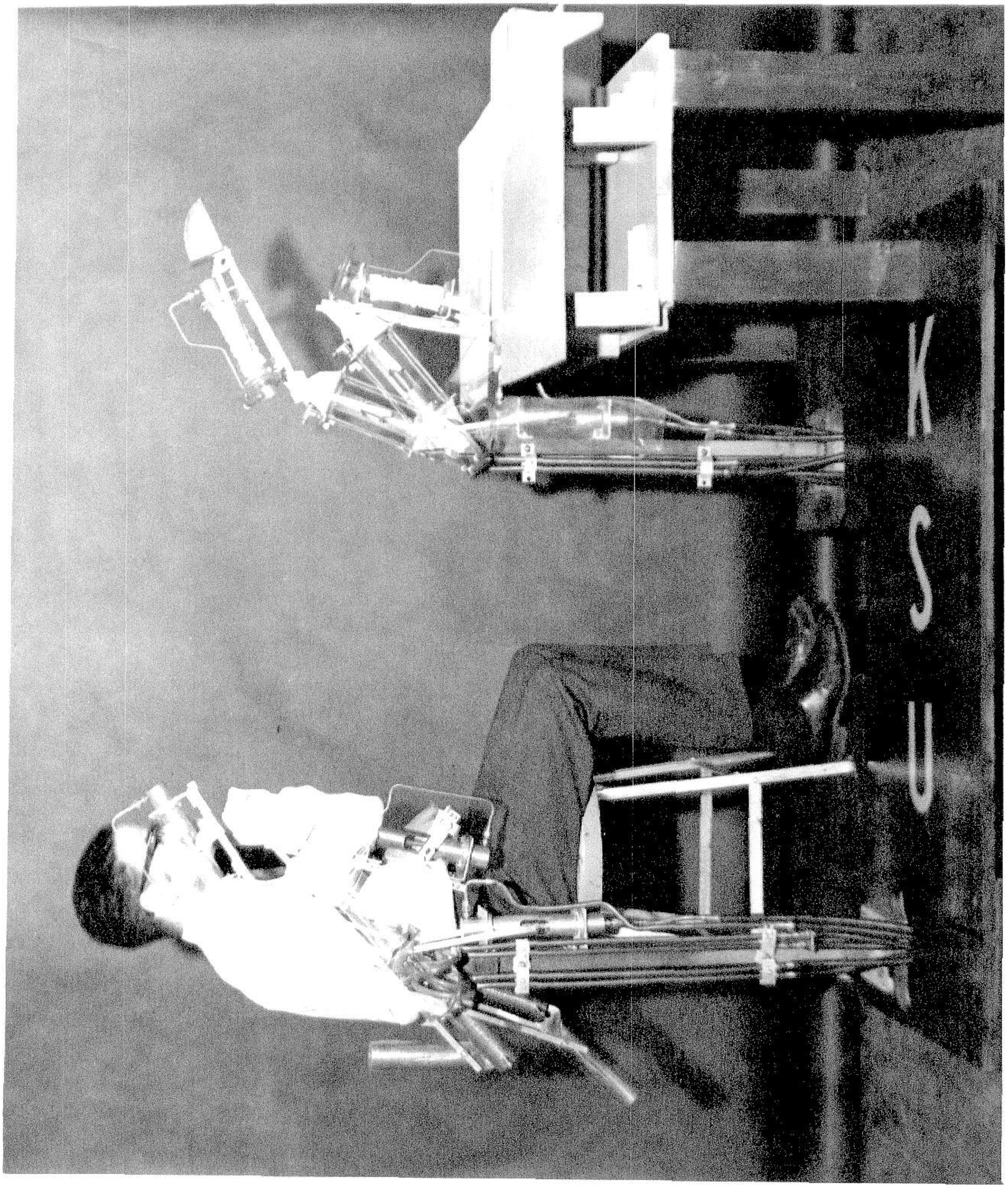
To avoid operator discomfort and fatigue, it is necessary to counterbalance the backhoe system. Since all slave forces are reflected to the master, the weight of the slave arm must also be counterbalanced.

The counterbalance mechanism has two parts. The first is called the upperarm and the second is called the forearm of the counterbalance. The forearm of the counterbalance is pinned to the upperarm of the counterbalance and moves in correspondence with the forearm of the master. The counterbalance is shown schematically in Fig. 7 and photographically in plate III and plate IV as a part of the model. Since force is reflected back to the

EXPLANATION OF PLATE III

Double exposure photographic view showing the correspondence between the motions of the master and the slave, and the workstation.

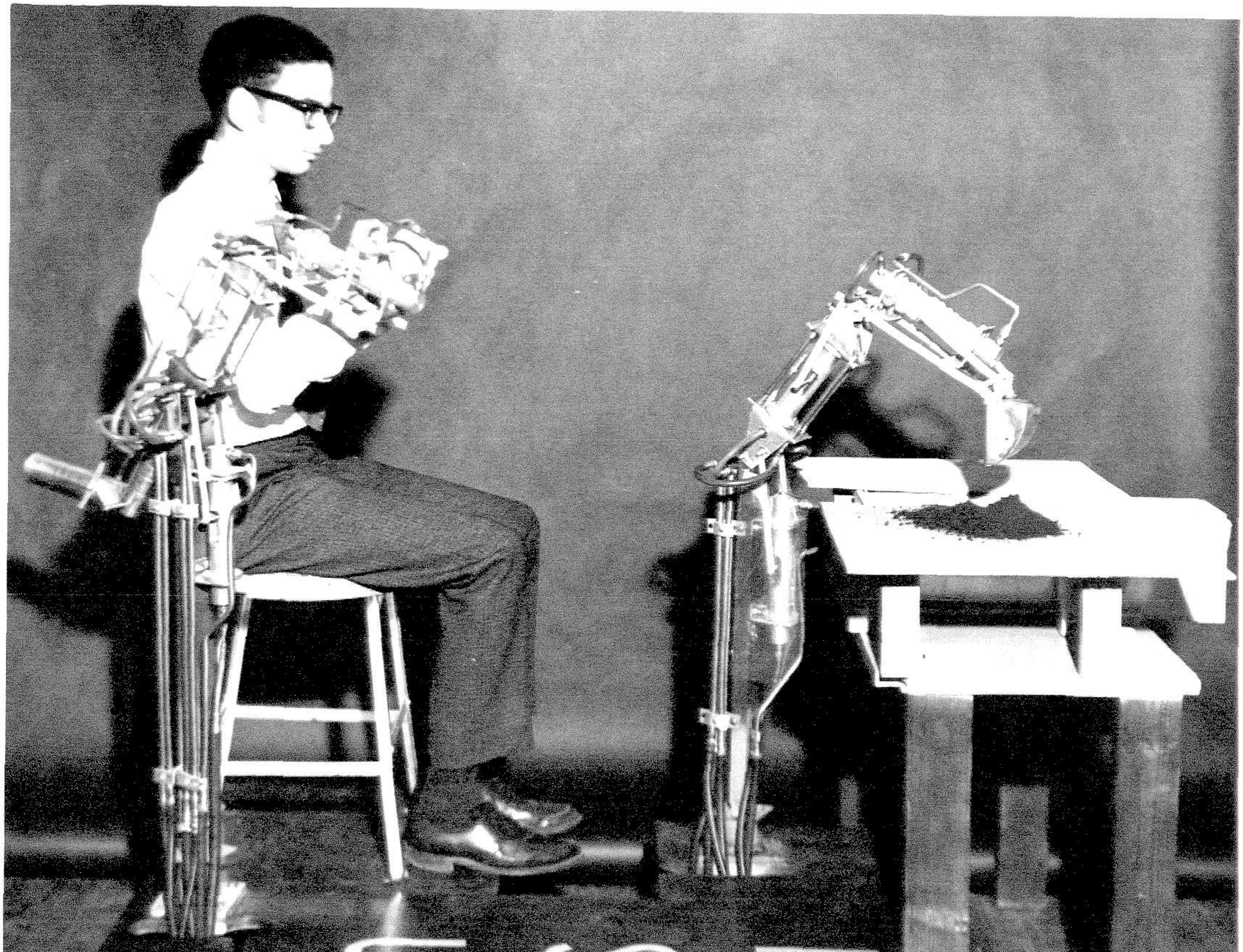
PLATE III



EXPLANATION OF PLATE IV

Photographic view showing the model in operation.

PLATE IV



master side, slave forces to be counterbalanced are considered as acting at the master side as shown schematically in Fig. 8-a.

Calculations of the weights and dimensions of the counterbalance are carried out in three steps. First, the system is considered as consisting only of the upperarm of the maste, of the slave, and of the counterbalance. In the second step, the complete system is investigated with all the fore-arms in a vertical position. In the last step, all arms are considered in an arbitrary and consistent position. The basis for this procedure will be clear when the three steps are carried out.

1. In this step, the system is considered consisting of only three upperarms as shown in Fig. 8-b. Assuming that the center of gravity of each arm lies in the middle of it, and taking the moments of all external forces around the point "O", results in the equation

$$W_{1_c} \times \frac{1}{2} \ell_{1_c} \cos\theta = W_{1_m} \times \frac{1}{2} \ell_{1_m} \cos\theta + W_{1_s} \times \frac{1}{2} \ell_{1_s} \cos\theta \tag{1}$$

where

W_{1_c} = weight of the upperarm of the counterbalance*
W_{1_m} = weight of the upperarm of the master
W_{1_s} = weight of the upperarm of the slave
ℓ_{1_c} = length of the upperarm of the counterbalance
ℓ_{1_m} = length of the upperarm of the master
ℓ_{1_s} = length of the upperarm of the slave
θ = angle of inclination of the upperarms

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*See Appendix A for the list of symbols.

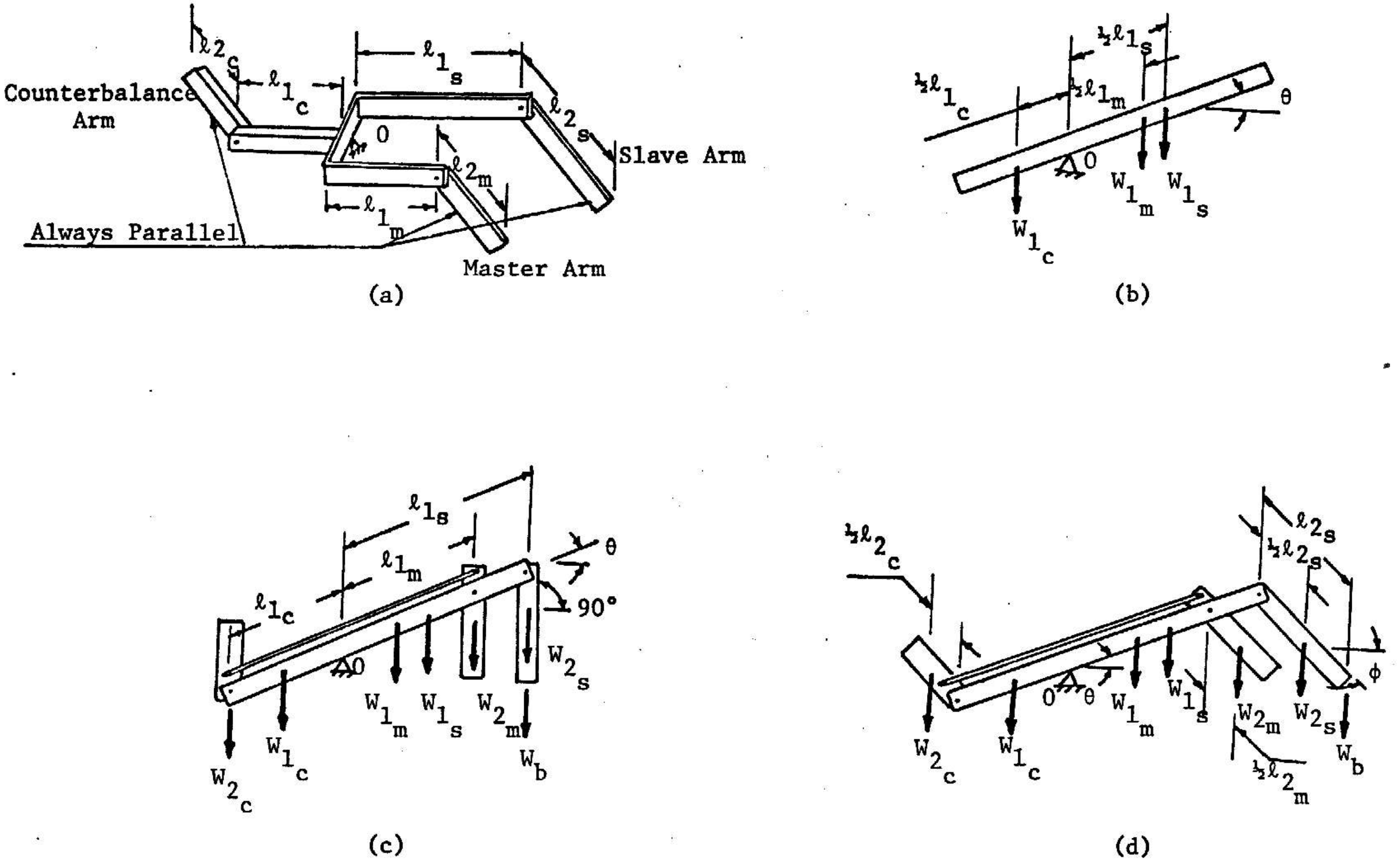


Fig. 8. Simplified Mechanism for Counterbalance Calculations.

By assuming a reasonable value of ℓ_{1_c}, W_{1_c} can be determined from equation (1). It is desirable to choose ℓ_{1_c} small to avoid large inertia torques. Up to this step, the system shown in Fig. 8-b is balanced for all values of θ.

2. In this step the complete system is taken into consideration, but all the forearms are held in a vertical position regardless of the value of the angle θ. This is shown in Fig. 8-c. The reason for doing this is to make the ratio of the horizontal distances of the center of gravity of each vertical link measured from the pivot point "0" is independent of θ. This greatly simplifies the analysis by eliminating the variable "ℓ_{2_c}". The moment equation about point "0" is now

$$W_{2_c} \times \ell_{1_c} \cos\theta + W_{1_c} \times \frac{1}{2}\ell_{1_c} \cos\theta = W_{1_m} \times \frac{1}{2}\ell_{1_m} \cos\theta + W_{1_s} \times \frac{1}{2}\ell_{1_s} \cos\theta$$
$$+ W_{2_m} \times \ell_{1_m} \cos\theta + W_{2_s} \times \ell_{1_s} \cos\theta$$
$$+ W_b \times \ell_{1_s} \cos \qquad (2)$$

where

W_{2_c} = weight of the forearm of the counterbalance
W_{2_m} = weight of the forearm of the master
W_{2_s} = weight of the forearm of the slave
W_b = weight of the bucket.

From equations (1) and (2), equation (3) can be written as:

$$W_{2_c} \times \ell_{1_c} = W_{2_m} \times \ell_{1_m} + W_{2_s} \times \ell_{1_s} + W_b \times \ell_{1_s} \qquad (3)$$

which determines the value of W_{2_c}. This value of W_{2_c} will maintain the system balanced in this special position. Up to this step, the complete system is balanced only when the three forearms are vertically oriented. The last step is to consider arbitrary positioning to determine ℓ_{2_c}.

3. In this step, the system is considered in a general position as shown in Fig. 8-d. Since the bucket is small in size compared to the arms, its center of gravity is considered to be at the far end of the forearm of the slave regardless of bucket orientation in space. For this configuration the moment equation is

$$
\begin{aligned}
W_{2_c}\left(\frac{1}{2}\ell_{2_c}\cos\phi + \ell_{1_c}\cos\theta\right) + W_{1_c} \times \frac{1}{2}\ell_{1_c}\cos\theta = {} & W_{1_m} \times \frac{1}{2}\ell_{1_m}\cos\theta \\
& + W_{1_s} \times \frac{1}{2}\ell_{1_s}\cos\theta \\
& + W_{2_m}\left(\frac{1}{2}\ell_{2_m}\cos\phi + \ell_{1_m}\cos\theta\right) \\
& + W_{2_s}\left(\frac{1}{2}\ell_{2_s}\cos\phi + \ell_{1_s}\cos\theta\right) \\
& + W_b\left(\ell_{2_s}\cos\phi + \ell_{1_s}\cos\theta\right) \qquad (4)
\end{aligned}
$$

where

ℓ_{2_c} = length of the forearm of the counterbalance

ℓ_{2_m} = length of the forearm of the master

ℓ_{2_s} = length of the forearm of the slave

ϕ = angle of inclination of the forearms.

From equations (1), (3), and (4), equation (5) may be written as:

$$W_{2_c} \times \ell_{2_c} = W_{2_m} \times \ell_{2_m} + W_{2_s} \times \ell_{2_s} + 2W_b \times \ell_{2_s} \qquad (5)$$

which determines the value of ℓ_{2_c}.

It is worthwhile to mention that by increasing the weight of the counterbalance, the operator might not have to support even the weight of his own arm. The counterbalance designed in the above way resulted in a model which is approximately but not perfectly balanced. This stems from the simplifying assumptions made in the analysis and may easily be corrected by slight adjustments of the counter weights.

Hydraulic Circuit

The complete backhoe model has three separate but similar closed hydraulic circuits, one for each of three degrees of freedom. This system was chosen because it provides inherent position control and bilateral force reflection, low compliance and is simple and inexpensive to construct. Choice of a working fluid is based on the need of low compliance, low viscosity for low pressure drops, availability and low cost, the ease with which the system may be pressurized, and finally convenience. Water fulfills these requirement admirably and is readily available under pressure. To reduce the compressibility due to entrapped air in the working fluid and to avoid wrinkles in the bellofams, the system was pressurized to 30 - 40 psi at all times. Working pressures are then superimposed on this steady pressure level. To further reduce compressibility in the system, copper and reinforced rubber tubing are used at all points where flexibility is not required. Plastic tubes are used to allow the arms to rotate freely relative to each other and to see whether or not there is entrapped air in the circuit. The hydraulic circuit is shown schematically in Fig. 9.

To prepare the system for operation, it is necessary to fill each circuit with water, remove air bubbles, pressurize the system and then index or register the master and the slave. To fill the system with water and remove air, the actuators and the tubes must be turned upside-down depending on where air bubbles are located. Also moving the pistons eases the operation of collecting air bubbles near the circuit opening where they can be driven out. Open valves A and B and apply pressure to the system. Close valve A. The system is now filled and pressurized but not registered. To register the system, move one master piston rod while keeping the slave counterpart stationary. When the position of the master and slave are identical, close valve B to maintain the desired register. This procedure must be repeated for each circuit.

As mentioned before, three of the motions of the master are transmitted hydraulically to the slave by means of the closed hydraulic circuits discussed above. The swing motion is transmitted mechanically through two pulleys and a belt to the slave. The diameters of the pulleys are equal, so a one to one correspondence in the swing motion in the system is achieved. The belt transmits forces, so the system is bilateral in this degree of freedom, beside being bilateral in the other three degrees of freedom.

As a summary of the above discussions, the four-degree of freedom master-slave backhoe model discussed above consists of few articulated links. Three of the motions of the master are transmitted hydraulically through

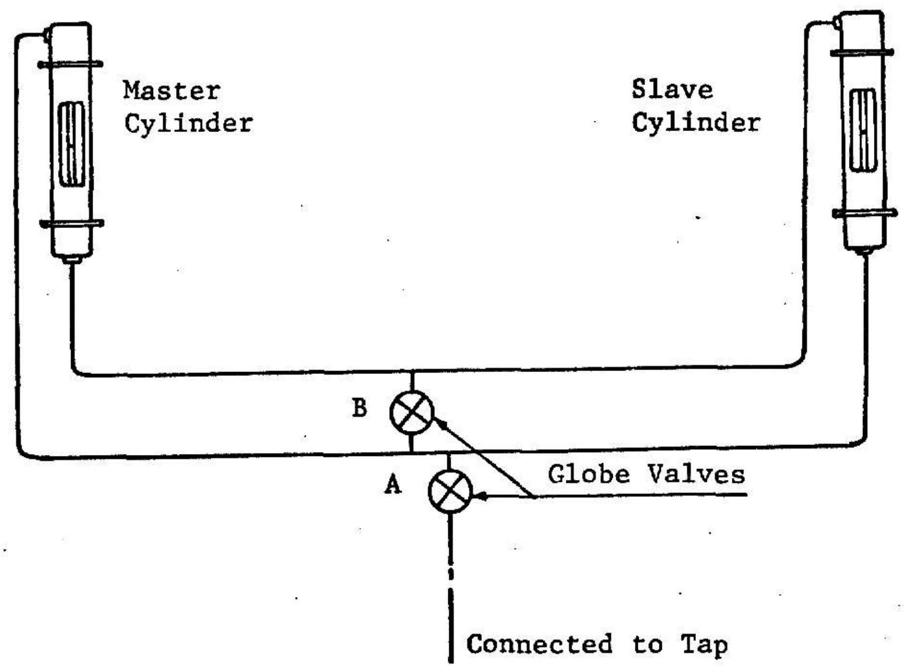


Fig. 9. Hydraulic Circuit.

three similar but separate hydraulic circuits to the slave. The fourth motion is transmitted mechanically. The system is bilateral in force reflection. A composite counterbalance on the master side balances the entire system.

CHAPTER IV

EXPERIMENTAL EVALUATION OF BACKHOE MODEL

In Chapter III the design of a complete master-slave controlled backhoe model was discussed. As a basis for evaluating the backhoe control concept and design embodied in that model, a simple experiment was carried out using each of a few test subjects. This chapter covers the experiment design and the results obtained from the experiment.

The various results to be obtained from an experimental study were outlined in Chapter III and are reiterated below for convenience. These results include:

1. Feasibility of the control concept.
2. Learning response of operators.
3. Control precision with new control system.
4. Design data for design of new models or of full sized units.
5. Operator reaction to control concept and to the model.
6. Comparison data for future studies.

As a basis for experimental evaluation of the backhoe design, it is necessary to provide some sort of typical backhoe task for the operators to perform. The task chosen for this study is discussed below.

Task

The task was to use the backhoe model to remove damp foundry sand from a specially designed box and place it beside that box. Box design will be explained in detail with the work station. By using foundry sand, the forces reflected to the operator were kept within reason. The subjects emptied the box ten successive times each day for three successive days. Each set of ten successive trials forms one session. Session times were scheduled randomly as shown in Table 1.

Apparatus

The apparatus used in this experiment are listed below:

1. The master-slave backhoe unit as shown in plate IV.
2. A specially designed wooden box served as a model for the ditch. It will be explained with the work station.
3. Five pounds of dry foundry sand mixed with about 100 cubic centimeters of water. This amount of material has a volume of about 124 $in.^3$.
4. An electronic timer, used to check time.
5. A seat for the subject to sit on.

Subjects

Seven male, right handed subjects from the Kansas State University student population, served as subjects. Five of the seven subjects were engineering students, two were not. Three subjects were paid $5.00 each. The other four subjects were student employees of the Department of Mechanical Engineering and were paid their regular salary for participating. All subjects were unfamiliar with the project. Table II shows the physical characteristics of the subjects.

TABLE 1

Random Arrangement of Sessions

Day Time \ Subject Number	1	2	3	4	5	6	7
8:00 AM	3*			2			1
8:30 "							
9:00 "			3				
9:30 "						1	
10:00 "		1					
10:30 "							
11:00 "					2		
11:30 "							
12:00 Noon	2			3		2	
12:30 PM					3		
1:00 "							2
1:30 "							
2:00 "		3	2	1			
2:30 "					1		
3:00 "		2					3
3:30 "							
4:00 "	1		1			3	
4:30 "							
5:00 "							

*These numbers refer to day number.

TABLE II

Physical Characteristics of the Subjects

Subject Number \ Physical Characteristic	Weight lb	Height ft	Height in	Upperarm Length in	Forearm Length* in	Elbow Height** in	Height of Eyes*** in
1	148	5	10	14	16½	0	32
2	150	5	10	14	17½	-3	31
3	140	5	10½	14½	16½	-1	30½
4	175	6	0	15	18	-2	31
5	160	5	10	15	17	-2½	31
6	145	5	10	14	17	-3½	28½
7	110	5	8	14½	16½	-1½	30

*Forearm length is defined as the distance between the elbow joint and the second joint of the third finger.

**Elbow height is defined as the distance between the elbow joint and the near joint of the upperarm of the follower rack, when the subject's arm is hung down and his forearm is horizontal.

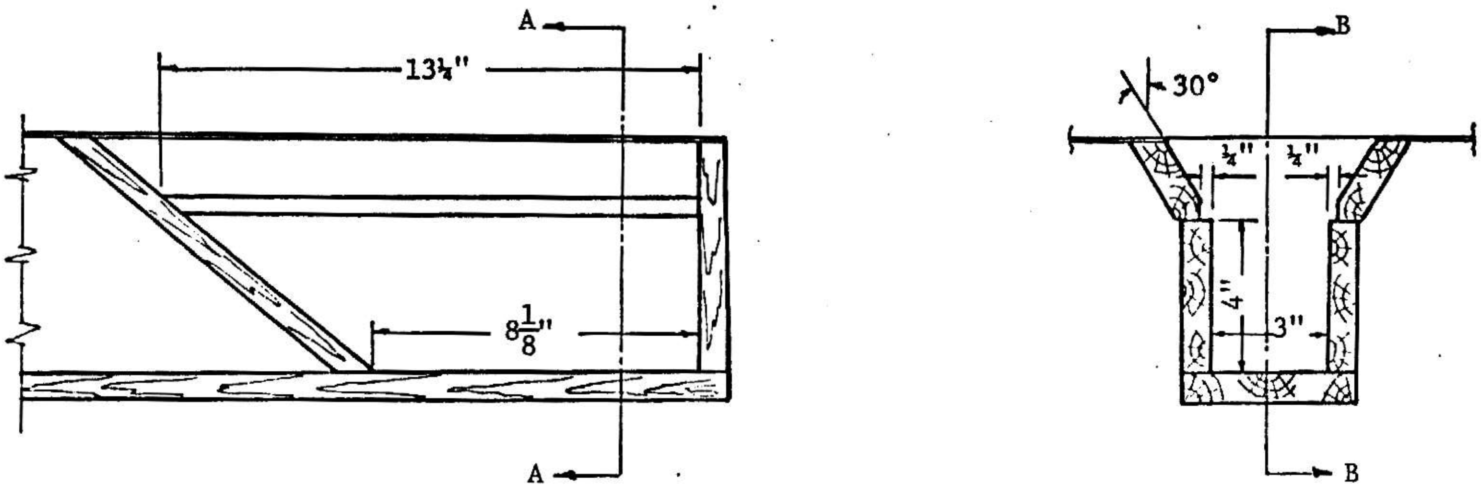
***The height of eyes is defined as the distance from the level of the subject's seat to his eyes.

Work Station

The working model is shown in Plate IV. Figure 7 indicates the main dimensions of the work station. The position of the slave relative to the master was chosen so that the angle of vision of the operator was expected to be close to that in a conventional backhoe. Because the width of the model arms is relatively large compared to the widths of the bucket and the ditch (the box), all subjects moved their heads a little to the left to improve visibility of the bucket and the ditch.

The box was made of wood and served as a model for the ditch. Figure 10 shows the box. The two inclined surfaces at the sides of the box were constructed to allow overflowing sand to fall back into the box. The two shoulders at the lower part of the inclined surfaces at both sides of the box, were included so that the bucket will enter the box only if it is placed over the exact center of the box. Thus, an operator who positions the bucket off center must redirect it. Since the bucket is 2 3/4" wide and the box is 3" wide, there is a clearance of only 1/8" at each side for a centered bucket. The far end of the box is inclined to avoid the difficulty of removing the sand from the far corner. This is illustrated in Figure 11. The box was filled to within 1/8" of the shoulders. To avoid excessive forces on the operator's hand and arm (requirement number 3), the sand was not compacted.

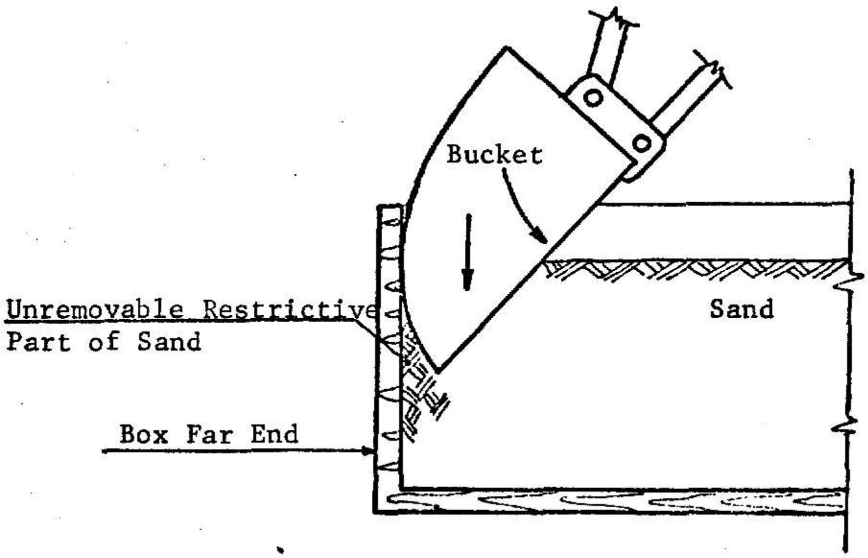
Two yellow lines painted to the right of, and parallel to the box, one 5 1/2" and one 12 3/4" away from the centerline of the box, were used as guidelines for dumping sand. Subjects were instructed to dump the sand between these lines.



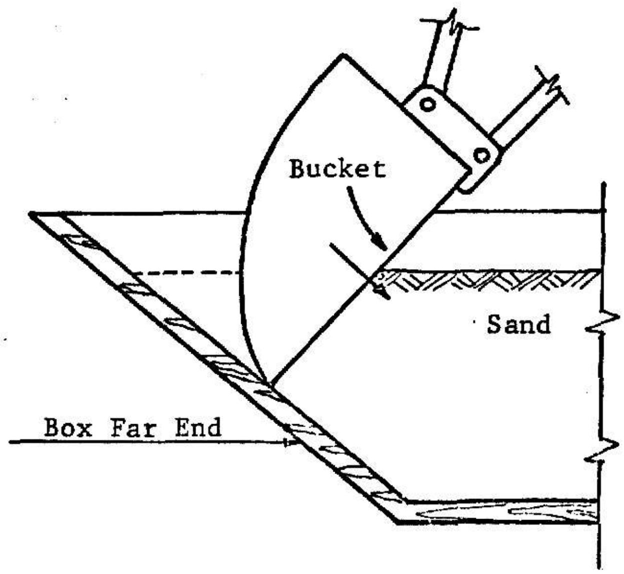
Sec. at B-B

Sec. at A-A

Fig. 10. Box Configuration and Main Dimensions.



(a) Wrong Design of Box Far End



(b) Right Design of Box Far End

Fig. 11. Box Far End.

Digging Profile

The digging profile of the model is defined as the range of positions which can be reached with the mechanism. The digging profile for the model is shown in plate V and was obtained by a continuous exposure photographic process.

Experimental Procedure

The experiment was conducted in one of the laboratories in the Department of Mechanical Engineering in Kansas State University on the 11th, 12th, 13th, 14th, 19th, 20th, and 21st of January, 1971. The temperature in the laboratory ranged from 66°F. to 80°F. The following was the procedure.

The sand was well mixed with water until it became cohesive but not wet. The sand was poured into the box without being pressed until it filled up to 1/8" below the level of the two shoulders. When a subject was ready for conducting the experiment, the experimenter* read an instruction sheet to him. The instruction sheet is shown in Appendix B. This instruction sheet was used, first, to familiarize the subject with the model and then to explain to him what he was to do. As indicated in the instruction sheet, the subjects had a trial first for practice. After the practice trial, the experimenter filled the box with the sand and the slave was set on the edge of the box at the near end of the box as shown in plate III. Then the experimenter stood beside the box to register time and observations on a data sheet. The experimenter then signalled for the beginning of sand removal from the box and, at the same time, he started the electronic timer.

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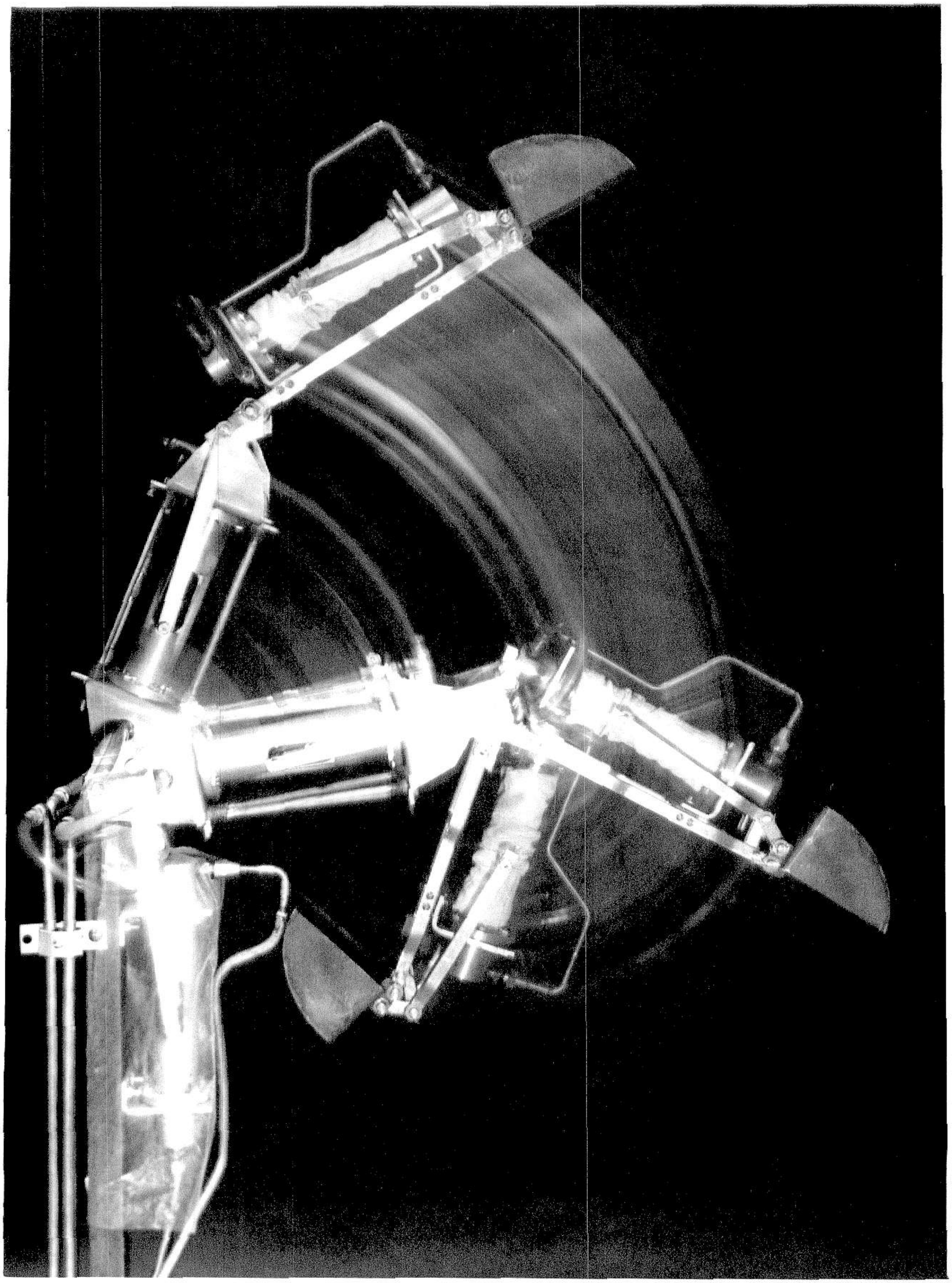
*The author was the experimenter.

EXPLANATION OF PLATE V

Continuous exposure photographic view showing the digging profile of the slave.

PLATE V



When the experimenter judged the box to be empty, he signalled to stop and, at the same time, he stopped the electronic timer and recorded the elapsed time.

During each trial, the experimenter recorded the number of cycles required to empty the box and the number of times the subject had to reposition the bucket over the box because of an incorrect initial position. Also he recorded general observations about the subjects and their operation of the system.

To begin a new trial, the experimenter poured the sand back into the box and repeated the previous procedure. No instructions were given to the subjects at the beginning of the second and third sessions. After the end of the final session, the experimenter asked each subject the questions indicated in Appendix C and recorded his answers.

EXPERIMENTAL RESULTS

Table III indicates the time required to remove the sand from the box for each subject, in each trial and the average value of the time for the seven subjects at each trial. Figure 12 shows the learning curve, i.e., average time versus trial number for the group of seven subjects. The curve was obtained by drawing a smooth curve through the data by eye. The limits of plus and minus one standard deviation for some trials are also shown. The value of the standard deviation for the sample at each trial is shown in Table IV. The standard deviation is defined by:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i-M)^2}\quad, i=1, 2, \ldots, n$$

TABLE III

Time of Performing the Task*

Trial Number \ Subject Number	1	2	3	4	5	6	7	Av. Time
1	2.366	3.000	2.750	2.650	3.100	2.550	4.000	2.917
2	2.084	2.533	2.819	2.568	1.835	1.700	3.150	2.385
3	1.837	1.683	2.869	2.334	2.350	1.468	2.818	2.195
4	1.800	1.850	2.650	1.968	2.067	1.184	3.284	2.115
5	1.466	1.500	2.733	1.684	1.194	1.167	2.367	1.731
6	1.433	1.333	2.274	1.550	1.217	0.918	2.568	1.614
7	1.284	1.200	2.150	1.517	1.267	0.970	2.835	1.604
8	1.134	1.733	1.800	1.150	1.033	1.084	1.950	1.412
9	1.067	1.333	1.667	1.450	1.000	0.900	2.194	1.373
10	0.884	1.050	1.717	1.800	1.217	1.050	1.818	1.363
11	1.500	1.100	1.784	1.886	1.234	1.067	1.734	1.473
12	1.150	0.783	1.416	1.783	0.818	0.850	1.317	1.160
13	1.084	1.000	1.267	1.700	1.000	1.217	1.234	1.215
14	0.934	0.834	1.500	1.634	1.017	0.800	0.982	1.100
15	1.017	0.768	1.384	1.583	0.818	0.834	1.067	1.068
16	0.970	0.683	1.134	1.784	0.718	0.918	1.317	1.075
17	0.834	0.634	1.134	1.869	0.618	0.970	1.083	1.021
18	0.866	0.834	1.134	1.600	0.633	0.818	1.017	0.986
19	0.866	0.650	1.067	1.533	0.668	0.800	1.134	0.960
20	0.818	0.650	0.968	1.868	0.600	0.900	1.368	1.025
21	1.200	1.017	1.500	1.300	0.650	0.850	1.167	1.098
22	0.934	0.650	1.100	1.200	0.600	0.782	1.167	0.918
23	0.785	0.633	0.918	1.450	0.633	0.650	1.000	0.867
24	0.968	0.530	0.900	1.267	0.600	0.818	1.050	0.877
25	1.000	0.485	0.967	1.250	0.568	0.667	1.050	0.856
26	0.732	0.583	0.800	1.100	0.534	0.782	0.950	0.783
27	0.768	0.600	0.870	1.083	0.633	0.667	0.918	0.792
28	0.650	0.568	0.918	1.117	0.667	0.633	1.017	0.796
29	0.718	0.550	0.768	1.267	0.618	0.718	1.067	0.815
30	0.718	0.500	0.900	0.850	0.618	0.800	1.117	0.786

*All values of time are in minutes.

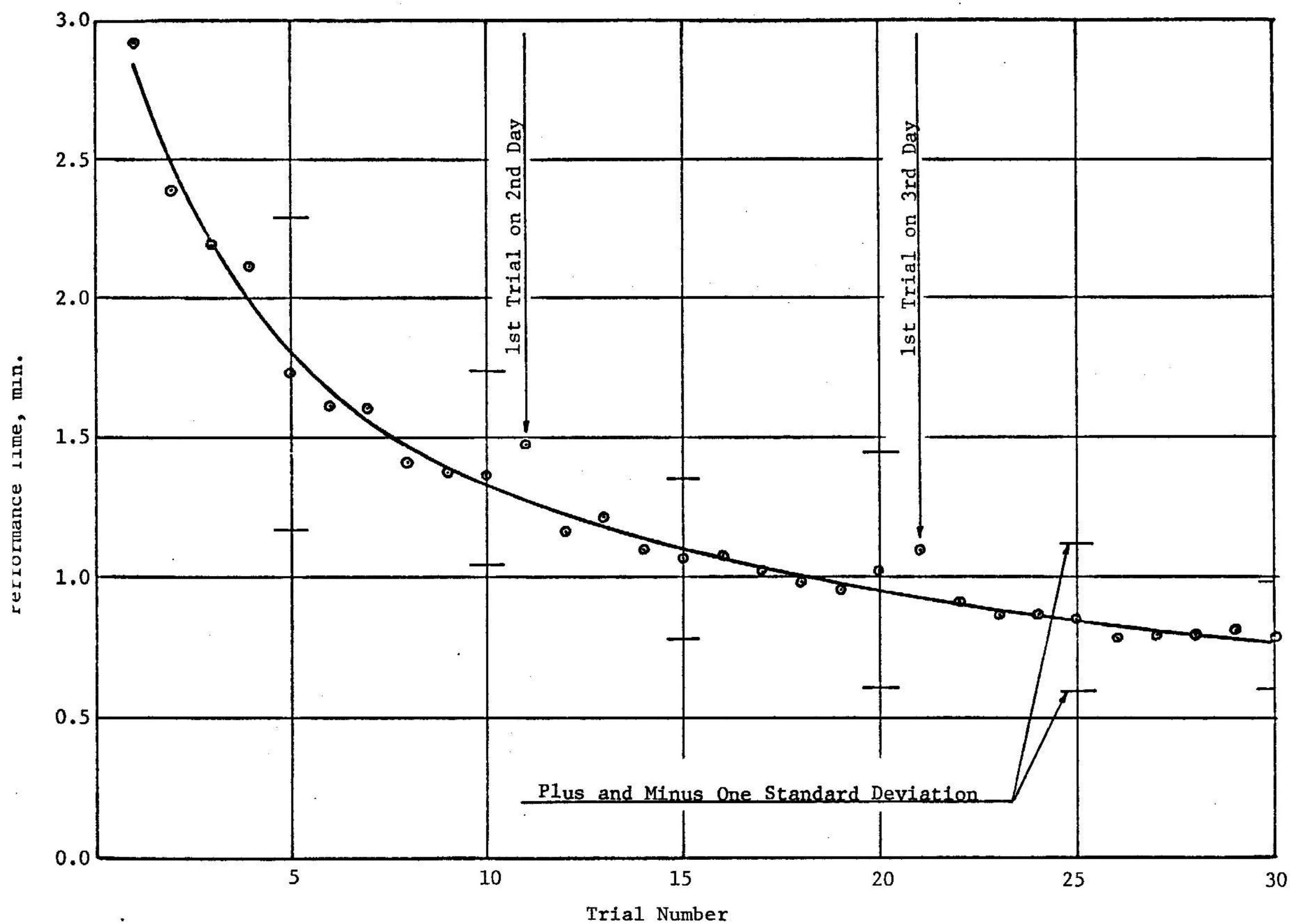


Fig. 12. Learning Curve.

TABLE IV

Mean and Standard Deviation

Trial Number	Mean	Standard Deviation
1	2.917	0.500
2	2.385	0.455
3	2.195	0.508
4	2.115	0.622
5	1.731	0.552
6	1.614	0.548
7	1.604	0.610
8	1.412	0.366
9	1.373	0.418
10	1.363	0.371
11	1.473	0.316
12	1.160	0.345
13	1.215	0.224
14	1.100	0.286
15	1.068	0.286
16	1.075	0.355
17	1.021	0.394
18	0.986	0.290
19	0.960	0.290
20	1.025	0.416
21	1.098	0.265
22	0.918	0.228
23	0.867	0.274
24	0.877	0.237
25	0.856	0.263
26	0.783	0.182
27	0.792	0.164
28	0.796	0.202
29	0.815	0.239
30	0.786	0.187

where

σ = the standard deviation

n = the number of measurements

x_i = the measurement

M = the mean of the x_i

Table V indicates the number of cycles in which the operator missed positioning the bucket over the box for each subject in each trail. The average number of misses for the seven subjects (normalized with respect to the average number of cycles for the seven subjects), in each trial and in each day are also shown. Figure 13 shows a plot of these average number of misses in each trial and in each day versus trial number.

DISCUSSION

Learning Curve

For the test conducted on the seven subjects, it is obvious that they learned very quickly. The time required to perform the task decreased from an initial value of about 3 minutes down to about 0.8 minutes at the end of thirty trials. When conducting the experiment, those 30 trials took, for each subject, not more than 1 1/2 hours. On the basis of net time, an average of only about 38 minutes was required to complete 30 trials.

As was expected before conducting the test the subjects took more time in performing the task in the beginning of the second and third days than at the end of the first and the second days respectively. This is shown clearly in Figure 12. One can notice that this occurred only in the first trial in the second and third days, but very soon the subjects regained their previous skill and continued along a smooth learning curve as if there

TABLE V

Repositioning the Bucket Over the Box*

Trial Number \ Subject Number	1	2	3	4	5	6	7	Av. Number Per Trial**	Av. Number Per Day**
1	1	6	3	2	2	3	3	0.345	
2	2	2	4	1	3	3	2	0.309	
3	2	3	0	1	4	2	0	0.226	
4	1	4	1	2	2	1	3	0.264	
5	0	2	1	1	2	2	2	0.204	0.236
6	0	4	1	0	1	2	1	0.188	
7	2	4	2	0	4	2	1	0.288	
8	2	1	2	1	2	2	1	0.239	
9	0	2	1	1	3	1	1	0.196	
10	0	2	0	0	2	0	1	0.098	
11	1	2	0	2	1	1	1	0.150	
12	2	2	1	3	2	1	1	0.255	
13	1	2	1	0	2	1	0	0.140	
14	1	4	2	0	0	0	0	0.140	
15	0	1	1	0	2	2	0	0.218	0.172
16	2	3	0	0	3	1	1	0.208	
17	3	1	0	0	1	2	1	0.166	
18	1	2	1	1	2	1	0	0.169	
19	4	1	0	0	0	0	0	0.103	
20	2	2	0	2	0	2	0	0.163	

*The average number of cycles of the bucket per trial is about 7.

**These numbers are normalized.

TABLE V (Continued)

Repositioning the Bucket Over the Box*

Trial Number \ Subject Number	1	2	3	4	5	6	7	Av. Number Per Trial**	Av. Number Per Day**
21	0	1	1	1	0	1	1	0.101	
22	1	1	0	0	0	0	1	0.066	
23	2	1	1	0	2	1	0	0.149	
24	3	1	1	1	2	1	1	0.213	
25	1	0	0	0	1	0	2	0.087	0.109
26	0	1	0	0	0	3	0	0.089	
27	0	1	0	0	1	2	0	0.085	
28	0	1	0	0	0	0	2	0.069	
29	1	2	0	0	0	1	2	0.128	
30	0	1	0	0	0	2	2	0.103	

*The average number of cycles of the bucket per trial is about 7.

**These numbers are normalized.

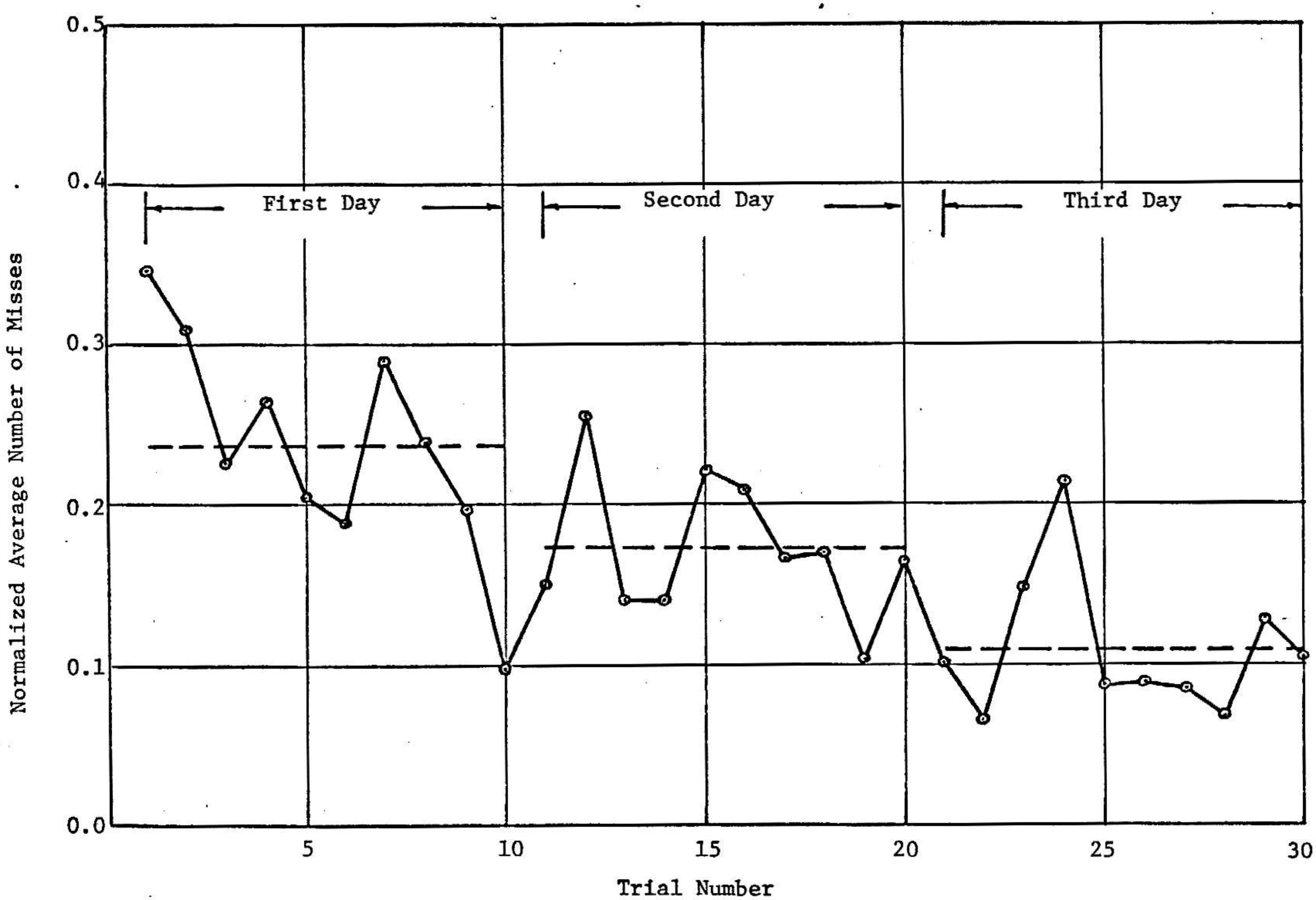


Fig. 13. Control Precision Curve.

were no layoff period between sessions. These decreases in performance are attributed to a degradation of skill due to the layoff. It is evident from Figure 12 that 30 trials are enough to reach near maximum performance. It is expected that with more trials, the performance time would decrease to near 0.7 minute and remain constant at this peak proficiency.

Control Precision

As shown in Figure 13, the normalized average number of misses decreased as the trial number increased. This is another indication of learning. It is believed that for well trained subject, the average number of misses will vary somewhat in proportion to the rate at which the subject works. In this experiment, both the number of misses and performance time decreased with practice.

Experimenter Observations About the Experiment

The following observations were made while conducting the experiment.

1. The subjects directed their attention to the motion of the bucket rather than to what they were doing with their own hands.
2. It was noticed, as mentioned before, that all subjects moved their heads a little to the left to improve visibility of the bucket and the ditch. This is attributed to the relatively large width of the slave arms compared to width of the bucket and the ditch.
3. The subjects usually poured the sand between the two yellow lines, except a few times when the sand was poured either on or outside the lines. It is believed that this was not due to insufficient skill of the subjects, but due to the insufficient inward rotation

of the bucket which caused sand to fall out as a result of arm movement. The subjects did not always follow item number 5 in the instruction sheet which asked that they pour the sand adjacent to the place from which it was removed. Generally, they poured the sand near the middle third of the box.

4. Most of the subjects made comments showing the pleasure and interest with which they operated this system.
5. It was noticed that four degrees of freedom were actuated simultaneously by four of the subjects in the second and third days when pouring the sand. One subject learned in the first day how to actuate all four degrees of freedom simultaneously when emptying the bucket. It was noticed also that early in the first day two or three degrees of freedom were actuated simultaneously by most of the subjects when placing the bucket into the box.
6. As subject number 6 started his first few trials, he mentioned that it was easier for him to operate a conventional backhoe rather than operating this model because the conventional backhoe does not require exerting muscular effort. But he mentioned that this difficulty of operation is because this model is not powered. After finishing the thirty trials, the experimenter asked him about which system he would like to operate if both of them were available. The answer was "this model". It is to be noted that this subject had operated a backhoe before, for about 1 1/2 hours.
7. Subject number 4 misused the model in the first day, so the experimenter asked that he treat the model more gently.

Subjects Response to Questions

The first question was, "How did you like this system?". The common answer for this question was that they liked it and they very soon became familiar with it.

The second question was, "Was it comfortable in operating it or not?". The common answer to this question showed that the model was comfortable. Five of the subjects mentioned that it was hard to rotate the handle. It is believed that this difficulty encountered by the subjects is attributed to three things. The first is that some of the subjects did not hold the handle correctly. Their thumbs did not wrap around the handle as they should for correct operation. The second, as mentioned in Chapter III, is that the mechanical disadvantage between the handle and the bucket necessitates large torques on the handle. The third is that some of the subjects did not adjust the bucket to the correct orientation for starting a dig cycle.

The third question was, "What kind of troubles did you face?". As a response to this question, four of the subjects mentioned that sticking of the bucket in the box was a problem. It is believed that the bucket got stuck because of the accumulation of the sand between the bucket and the box on both sides. Other difficulties encountered occasionally include overflow from the bucket and operation near the far end of the box. The latter problem will be discussed later with the experimenter observations about the model.

The fourth question was, "Do you have any other comments you like to mention?". The common answer for this last question was that the idea is good. Some of the subjects did not have any comments.

Experimenter Observations About the Model

It is believed that the system worked successfully. A satisfactory degree of dexterity and accuracy of operation could be achieved. The degree of control was demonstrated by fastening chalk to the bucket and using the backhoe to write letters on a horizontal plane. The size of the letters was as that written directly by hand on a blackboard.

Because of the geometry of the master arm, a straight inward pull tends to extend rather than flex the forearm. This is illustrated in Figure 14-a. This difficulty may be overcome by applying a couple and a force at the same time thus flexing the forearm. This is indicated in Figure 14-b. It is to be noted that most of the subjects followed this procedure as the experimenter explained to them in the practice trial. It is to be noted that this was one of the difficulties encountered occasionally by some of the subjects and mentioned before with subjects response to questions.

During operation of the model, one of the belloframs failed. This failure may be attributed to rough piston-cylinder surfaces and lack of concentricity between piston and cylinder. After replacing the defective bellofram by a new one, the system has worked for more than 2000 cycles without failure.

Despite the great number of joints and sliding surfaces in the model, the friction forces were not significant compared to working forces. Also the retarding forces due to pressure drop in the pipes and tubes connecting the master and the slave were low compared to working forces. After many cycles of operation some of the joints are slightly worn but the backlash is not significant.

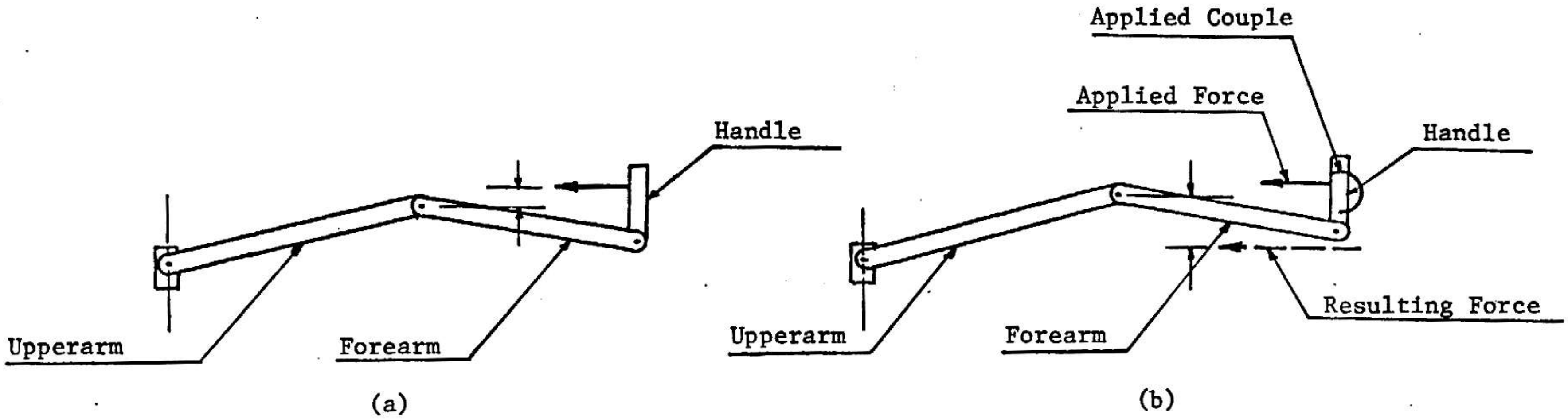


Fig. 14. Master Forearm Flexion and Extension.

CHAPTER V

SUMMARY, CONCLUSIONS, AND RECOMMENDATION

Summary

The attempt made in this investigation was to develop a model for a backhoe with a new type of control which provides the operator with a better and more natural control.

A manually powered model was built and tested to demonstrate the feasibility of the new control concept. The system consists essentially of a master arm which the operator holds and moves by his hand, and a slave arm which obediently follows the master. The slave arm is a scale model of the backhoe arms. Transmission of the forces and motions of the master to the slave and of the forces from the slave back to the master, takes place through three closed hydraulic circuits and one mechanical circuit. The system is bilateral and balanced, so the operator does not have to support the weight of either the master, or the slave arm.

An experiment was conducted with a group of inexperienced test operators to determine the feasibility of the control concept. The subjects were asked to use the model to remove sand from a box designed to serve as a model for a ditch. Each of the seven subjects emptied the box ten successive times each day for three successive days. The following is a summary of the results obtained from conducting the test.

1. The subjects rapidly learned how to use the model to remove the sand from the box. This task is similar to that done by a real backhoe. The time required to perform the task decreased from an initial value of about 3 minutes down to about 0.8 minute

at the end of the thirty trials which took, for each subject, not more than 1 1/2 hours, and on a basis of net time, they took about 38 minutes.

2. As an indication of learning and control precision, repositioning of the bucket over the box was observed. The box is only 1/4" wider than the bucket, so the subjects occasionally had to reposition the bucket. The ratio of the number of cycles in which the bucket was repositioned once or more over the box to the total number of cycles in each trial for the average subject decreased from about 0.35 to about 0.1 within the thirty trials and the daily average decreased from 0.24 to about 0.11 within the three days.

3. The answers of the four questions asked to the subjects show that they liked the model and it is in general comfortable to operate.

The following is a summary of the observations made while conducting the experiment.

1. Most of the subjects learned how to actuate several degrees of freedom simultaneously.

2. All subjects directed their attention to the slave arm rather than to the master arm.

3. The subjects moved their heads a little to the left to improve bucket and ditch visibility.

4. Most of the subjects held the handle correctly. They showed their interest in operating the model. Few of them did not hold the handle correctly.

Conclusions

The results obtained and the observations made on both, the model and the subjects when conducting the test, show that the subjects learned rapidly how to use the model and improved their control precision quickly. So, the conclusion is that the control concept is well feasible. It is expected that this success in building, operating, and testing the model will lead to a great development in many industrial equipment.

Recommendation for Further Studies

As mentioned before, the attempt made in this investigation was to develop a model for a backhoe with the new control concept inherent in it. Since the control concept was found to be feasible for the model, it is necessary to consider a full-size backhoe involving such a control concept. Of course this new system must be externally powered. The reason of recommending such an attempt is to enable one to compare two backhoes, one of the conventional type and the other involving the new control concept. The comparison must, not only include the performance of operators, but also include the cost and practicality. The components and operation of the recommended system is explained next.

The system consists mainly of two parts, the master which is the harness the operator is to hold, and the slave which is the backhoe arms, in this case. The master arm is recommended to have nearly the same configuration as that of the model developed and discussed in this thesis. Experience with the model shows that the handle must be modified to ease flexing the forearm, (Fig. 14).

As it is mentioned in Chapter III, for the slave to mimic the master, the control system must be a closed-loop control system. The main components of a suggested closed-loop force reflecting control system are shown in Fig. 15. Each degree of freedom will have a similar control system. Differences in position between master and slave result in bridge unbalance. This unbalance is amplified and used to derive a servo valve which controls flow to the slave actuator. This causes the actuator and hence the backhoe arm to move. The connection from the other side of the bridge to the moving joint of the slave causes the bridge to rebalance and all motion to stop when master and slave correspond in position.

Force reflection can be accomplished by a separate hydraulic circuit. Pressure on both sides of the actuating piston is transmitted through hydraulic lines to the differential-feedback cylinder. The difference in pressure in the lines produces a force in the differential-feedback cylinder piston which is transmitted through the feedback-force-ratio bar to the displacement-reducing cylinder. This force will be transmitted hydraulically to the master-control-cylinder producing a force which, because of the similarity of the master and slave arm, is proportional to the force experienced by the backhoe arm. The magnitude of the force reflected can be changed by changing the position of the supporting rollers of the feedback-force-ratio bar.

It is to be noted that this system is only a suggested system and no detail investigation has been done on it regarding practicality, cost, etc.. The feasibility of building such a position control system is demonstrated by a similar system successfully designed for a heavy duty manipulator, [12].

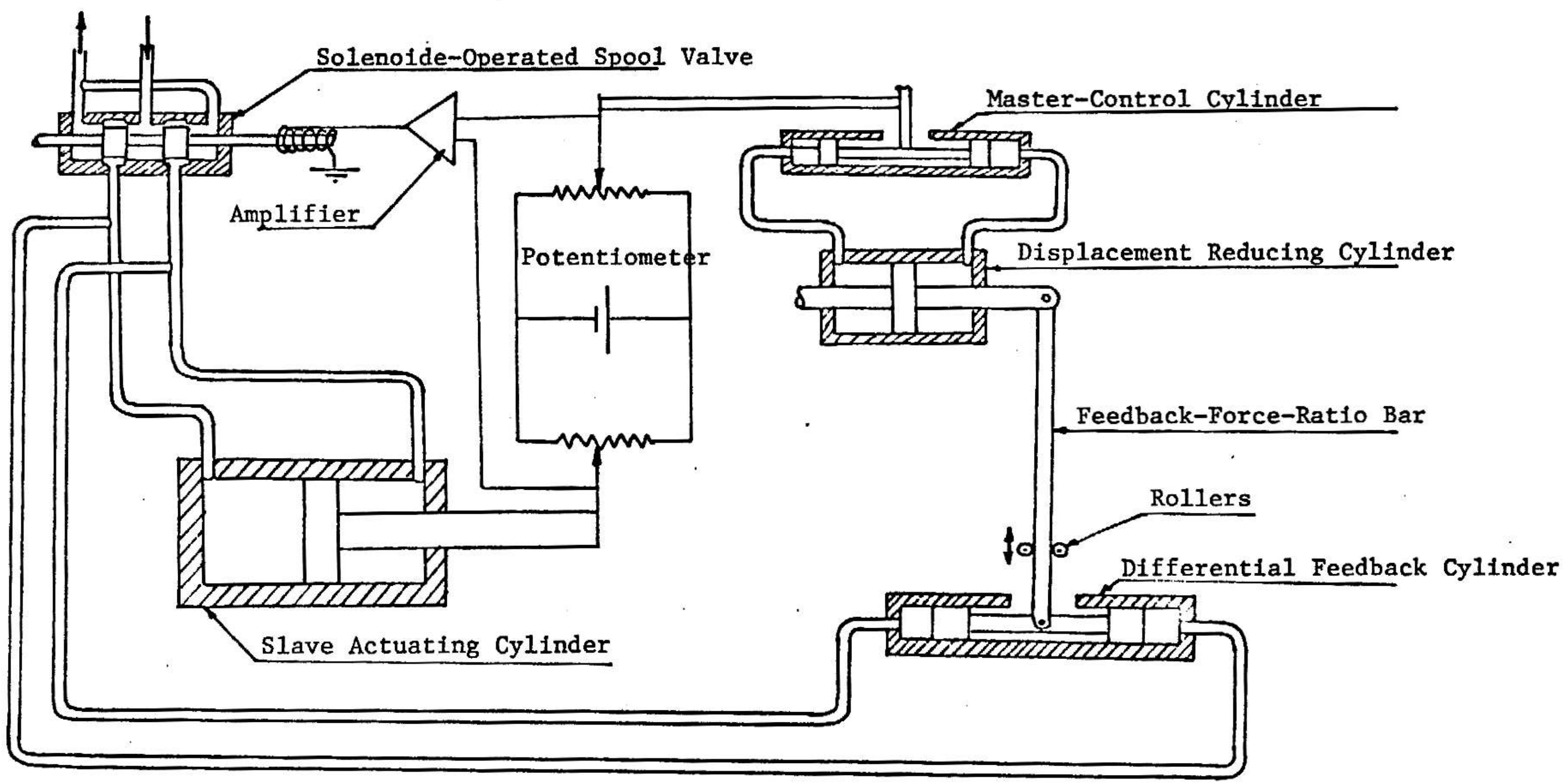


Fig. 15. Recommended Closed-Loop Force Reflecting Control System.

Also, the power steering mechanism of cars is another indication of the feasibility of building a powered position control system incorporating force reflection.

As mentioned in Chapter III, a four-degree of freedom backhoe can not dig ditches along any desired curve, or work in confined places (Fig. 4). It was shown in Chapter III that this was made possible for a six-degree of freedom backhoe. It was shown also in this thesis that an operator could operate the model with his right hand. There are still some more degrees of freedom in his right arm and hand that he did not use and can make use of. So it is recommended that the feasibility of a six-degree of freedom backhoe must be investigated.

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APPENDICES

APPENDIX A

NOMENCLATURE

Symbol	Definition
ℓ_{1_c}	length of the upperarm of the counterbalance, in.
ℓ_{2_c}	length of the forearm of the counterbalance, in.
ℓ_{1_m}	length of the upperarm of the master, in.
ℓ_{2_m}	length of the forearm of the master, in.
ℓ_{1_s}	length of the upperarm of the slave, in.
ℓ_{2_s}	length of the forearm of the slave, in.
M	the mean of the measurements, min.
n	number of measurements
W_{1_c}	weight of the upperarm of the counterbalance, lb_F.
W_{2_c}	weight of the forearm of the counterbalance, lb_F.
W_{1_m}	weight of the upperarm of the master, lb_F.
W_{2_m}	weight of the forearm of the master, lb_F.
W_{1_s}	weight of the upperarm of the slave, lb_F.
W_{2_s}	weight of the forearm of the slave, lb_F.
W_b	weight of the bucket, lb_F.
x	the measurement, min.
σ	standard deviation
θ	angle of inclination of the upperarms, degrees.
ϕ	angle of inclination of the forearms, degrees.

APPENDIX B

INSTRUCTION SHEET

This system is a model of a backhoe with a new type of control. A backhoe is a machine used primarily for digging ditches. This system consists of two main parts, namely, master and slave. This is the master and this is the slave.

You are supposed to sit beside the master and hold it as I'll do now.

There are four movements in the master. Notice that these movements are transmitted exactly to the corresponding parts of the slave. These are the four movements. Watch the slave at the same time. Also watch the range of each movement.

Now you may sit down and try moving the arms and I'll help you in doing this.

If you have any questions concerning how to move the arms, ask me.

The object of the task is to remove the sand from the box and place it beside the box as I am doing now.

Please follow these instructions in doing the task:

1. You will be asked to empty the box ten times today, ten times tomorrow, and ten times on the day after tomorrow.
2. Between each trial in each day, you can keep sitting on your seat, or sit anywhere in this room.
3. When you hear the start signal, you may begin removing sand from the box and pouring it between the two yellow lines.
4. Start at the far end of the box and work toward the near end.

5. Each bucket of sand should be poured between the yellow lines and beside the place from which it was removed.
6. When it becomes difficult to get any significant amount of sand in the bucket, you'll hear the stop signal, and you may stop.
7. Work at a rapid but comfortable pace and transfer the sand as quickly as possible without over exertion. Work carefully to avoid damaging the mechanism.

Now you may ask any questions concerning doing the job.

Now you may empty the box once for practice and I'll answer your questions while you are doing it. After you finish the trial, I'll again read you the instructions you have to follow.

APPENDIX C

QUESTIONS ASKED TO THE SUBJECTS

1. How did you like this system?
2. Was it comfortable in operating it or not?
3. What kind of troubles did you face?
4. Do you have any other comments you like to mention?

DESIGN AND EVALUATION OF A BACKHOE MODEL WITH A MASTER-SLAVE CONTROL

by

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B.Sc., Assiut University, Egypt, 1968

AN ABSTRACT OF A MASTER'S THESIS

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requirements for the degree

MASTER OF SCIENCE

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KANSAS STATE UNIVERSITY

Manhattan, Kansas

1971

ABSTRACT

Remote handling, as a part of materials handling field, has received noticeable attention in the last two decades. The attention has been due primarily to the need for advanced manipulators in such places as hot labs. Up to the present time, however, advanced manipulator principles have not been widely applied in routine materials handling equipment. The purpose of this thesis was to test the feasibility of applying these concepts to more mundane tasks. Because a backhoe is more anthropomorphic than most other industrial equipment, it was chosen as a test item for application of advanced manipulator principles.

In a conventional backhoe, the operator has four levers, each controlling the rate of motion of a given degree of freedom. To move the bucket from one location to another, the fastest and most efficient path is a smooth continuous curve between the locations. For the operator to move the bucket along this path, he must specify directions and speeds for several actuators simultaneously. With the four lever control, it is unlikely that an operator can control more than two simultaneously. Therefore a new integrated control system which allows the operator to effectively control all degrees of freedom simultaneously is proposed. A manually powered model was built and tested to demonstrate the feasibility of such a control concept. The system consists essentially of a master and a slave. The master is the control and the slave is a scale model of the backhoe arms. Communication of positions and forces between the master and the slave is accomplished by three closed hydraulic circuits and one mechanical linkage. The model is bilateral and balanced. Inexperienced operators were used in an

experiment. This experiment showed that the subjects rapidly learned how to use the model, the model demonstrated the idea and worked successfully, and the control concept investigated is well feasible.