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Handyman to Hardiman

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TO DESCRIBE a unique control system for application to earth-moving and material-handling equipment is the purpose of this paper. This method of control will provide machinery with human-like action that mimics an operator's natural motion. Such a closely coordinated man-machine system will exploit the union of man's superbly integrated sensory system with the tremendous power potential of machinery. In particular, force and position sensing will be transmitted between the man and the machine's effector (that is, scraping blade, toothed bucket, etc.).

Recent technological history is characterized by the rapid and widespread application of automatic control, data processing, and information and control theory. In spite of the impressive mechanization achieved to date, one area of outstanding potential remains to be exploited. The adaptive, reflex control of man can be transmitted directly to a mechanism, so that the mechanism responds as though it were a natural extension of the man. Such control is easy to achieve, compared to automatic control equipment.

The principle is sound and has been effectively demonstrated in mechanisms that are discussed in this paper.

HUMAN CONTROL VERSUS AUTOMATIC CONTROL

Significant advances in control and control theory promise startling mechanizations of tasks heretofore performed only by humans. In spite of these achievements and the expectation for continued progress, the difficulties of duplicating many feats of the human brain and nervous system still remain formidable. Consequently, many mechanical operations will not be automated for some time.

Until such time as information and control theory, and its associated technology match human capabilities in more than a few specialized fields, there is considerable opportunity for profitable symbiosis of man and machine. Moreover, as industrial processes rely more and more heavily on prompt and accurate machine response, the need for closer control coordination will become acute. The integration of man and machine into a mutually complementing system is one way of meeting the demand for improved control.

The human information and control system benefits from low weight, space, and power requirements, and a superb integration of the entire organism, so that all its parts work harmoniously and expeditiously. However, when it comes to mechanical or mental output involving speed, accuracy, and diligence (especially attention to repetitive detail), humans are notoriously poor performers. Furthermore, many specialized motor abilities can be acquired only after considerable motivation and learning. In those instances that require only the preceding characteristics, it is frequently best to do the entire job mechanically.

On the other hand, for tasks which up to now have required human qualities (for example, judgment, continuous sensory appraisal, force and position sensing, etc.), but mechanical effectors, the man-machine complex can be designed on an anthropomorphous (human in form) basis. The human element would be attached to a follower rack which would measure the angular positions of the applicable joints of the human element. The signals generated would be used to operate the similar, powered joints of the machine. Force and position feedback from the machine joints could also be provided to the follower rack.

A system using this approach is called a Cybernetic Anthropomorphous Machine (CAM). It is a cybernetic since

ABSTRACT

Man and machine can be combined into an intimate, symbiotic unit that will perform essentially as one wedded system. This Cybernetic Anthropomorphous Machine (CAM) will respond to irregular force and position patterns with the alacrity of man's information and control system coupled with the machine's power and ruggedness. A new and exciting area for the application of this control technique is in earth-moving and material-handling equipment.

it involves the use of applicable information and control techniques and theories. It is anthropomorphous since its effective members operate very much like those of a human organism in performing the required task. See Fig. 1. Based upon experimentation that has established beyond doubt the feasibility of fundamental principles, a number of these CAM systems have been developed.

MANIPULATORS

Manipulators are used to extend and augment man's capabilities in those tasks that require human judgment and control. Man's sensory assets and his complex manipulating ability guide the machine. However, the work and power output of the machine is not limited by the man's capabilities. Moreover, environments that are normally hostile to a human do not affect the machine.

The ability and efficiency of a manipulator depend on effective cybernetics, or adequate transmission of human sensory information between the operator and the task. Manipulative dexterity, proprioceptive position, kinesthetic force, and visual and audio sensing are factors that must be incorporated in a meaningful extension of man's capabilities.

In manipulative machinery, position and motion of the human arms and hands are followed by a servo system, which causes a mechanical analogue of the upper extremities to follow the human template. The human sensory and data processing systems, along with the servo itself, are used primarily as feedback loops in a highly integrated manner. The eye by direct viewing or television, the ear by direct or indirect listening and the tactile sense through the use of force feedback are used as sensors. Human proprioceptiveness is important. The natural muscular sense of position is exploited; the manipulator is isomorphic and mimics the operator's movements.

Motions which are impossible for a human can be accomplished by a manipulator. For instance, a remote manipulator might be required to rotate parts such as unscrewing a nut or bolt. The wrist joint or an additional joint in the forearm of the machine can be devised so that it will rotate continuously on command.

Fig. 2 is a photograph of "Handyman." This is a two-armed master-slave manipulator used for handling radioactive equipment. This photograph shows the operator in close proximity to the slave, which is whirling the hula-hoop. In action operating conditions where radioactive material is handled, a concrete barrier separates the master station and the slave. The only connection between the master and slave is an electrical control.

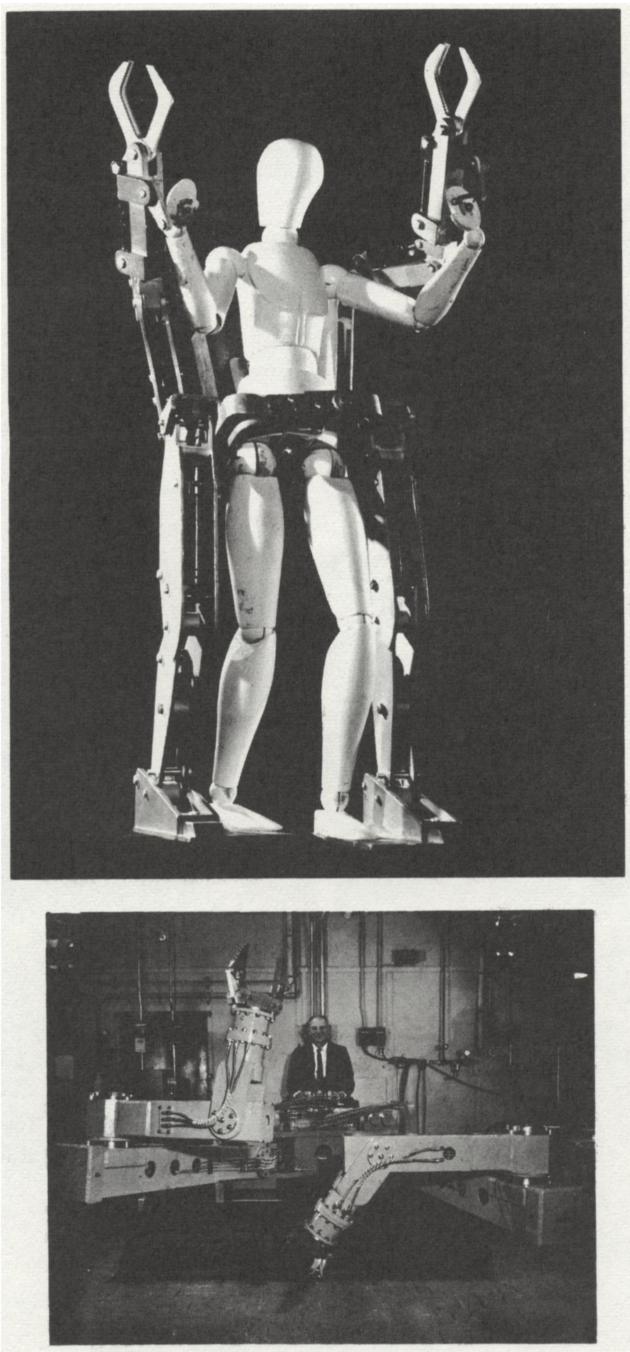

Fig. 1 - Examples of anthropomorphic machine development at General Electric Co.

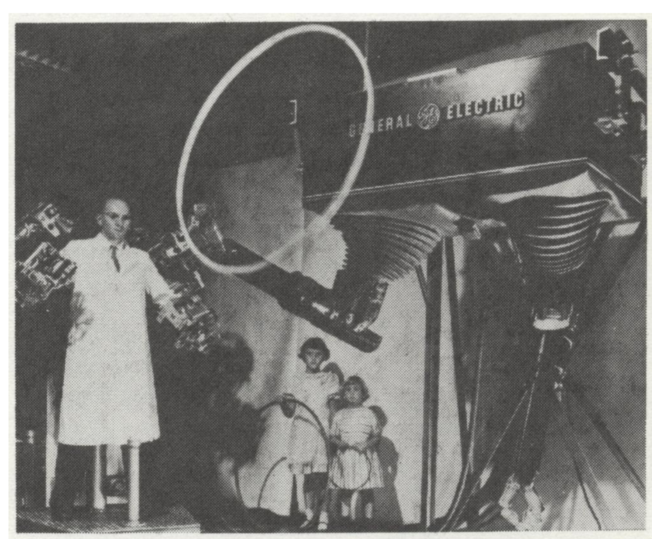

Fig. 2 - Handyman - an electrohydraulic force-reflecting manipulator

At the right-hand side of the picture is the two-arm slave unit; at left, the operator at the control station. The operator's hands and arms are in the control harness, and their natural motions are reproduced by the motions of the manipulator arms. The operator does not have to support the weight of the harness or of the slave, or even of his own arms, because the machine is designed to exactly counterbalance all these masses regardless of the arm position.

The mechanical arms and hands in human form are electrically connected to a harness worn by the operator. The system causes the mechanical limbs to mimic the actions of the man's arms and hands (that is, to follow the human template) while the man in turn receives signals from the machine conveying information about force and position. The machine is coupled to the man's sensory and motor system in such a way that the whole setup operates in a highly integrated manner through feedback of force and position information.

Handyman has ten motions in each arm. All these motions are hydraulically actuated by means of electric 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. In handling an object, the machine registers the positions and forces associated with the manipulation; this information is translated into electric signals and sent back to actuators attached to the operator, which convey to him forces proportional to those experienced by the machine. The operator's harness is called the follower rack.

The coupling is so direct and detailed that the man does not have to think about operating the machine. He simply concentrates on the manipulation task itself; he observes the actions of the mechanical arms and hands as if they were his own.

Handyman is a good example of merging man and machine, using the best capabilities of each. The value of the Cybernetic Anthropomorphous Machine (CAM) has been proven and the potential for CAM's in a variety of other applications is apparent. Terrestrial high radiation areas, outer space, and the ocean depths are locales where CAM's can be used. In the industrial world, earth moving, material handling, and manufacturing activities can be accomplished with manipulative CAM's.

Fig. 3 is a photograph of a similar device developed by Raymond Goertz of Argonne National Labs. The main difference between Handyman and this manipulator is that the latter is controlled with electromechanical rather than hydromechanical servos. It also has the added feature of television cameras mounted on the machine.

Two basic problems must be solved to fit CAM's into each type of application. One is the system concept design to provide the kinematics and appropriate psychophysical control properties needed. The second is the development of machinery suitable for the application.

Human Factors - The first problem area of psychophysics must be understood to appreciate the significance of human sensing and controlling with regard to performance. Man's capability for intricate manipulating and controlling is not readily appreciated because it is so familiar. Nevertheless, separation of man and task by a lever or pedal-controlled mechanical system causes a degradation of performance in terms of mechanical filtering of human sensing. Comprehension of human factors such as these is a key to the design of effective CAM's.

Consider the seemingly simple operation of opening a door. One grasps the doorknob and swings the door in an arc of a circle with the hinge axis at its center. The hand pulling the door must follow an arc lying in a plane at the level of the knob parallel to the plane of the floor; the pulling force must conform to the circumference of the circle described by the distance from the knob to the hinge axis. In doing this the hand, assisted by the human nervous system, is guided by the door's resistance to being pulled along any other path. In other words, the human motor system responds to a feedback of forces that must be interpreted. A strong robot, lacking any means of such interpretation and free to pull in any direction, might easily pull the door off its hinges instead of swinging it open. Similarly, the same robot, given a chair to carry, might pull it to pieces because of inability to sense or interpret the resistance of the chair's structure to being pulled apart. As another example, consider the problem of sliding a rod into a snugly fitting tube. A man can do this, even blindfolded, by trying various angles of insertion until he finds the one at which he can push the rod in without forcing it. A robot, on the other hand, would simply push hard at any angle and bend or crumple the rod.

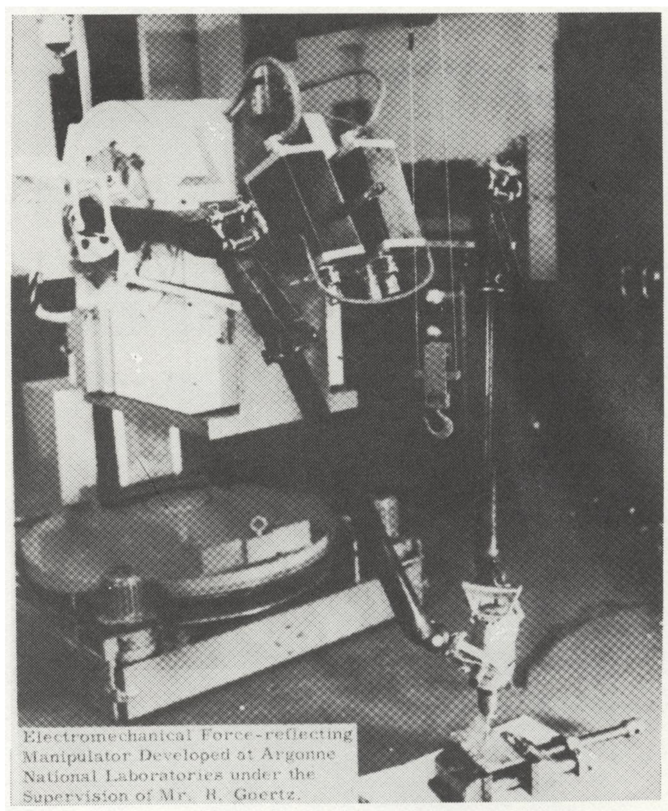

Fig. 3 - An electromechanical force-reflecting manipulator developed at Argonne National Labs

The concept involved here can be illustrated in another way. As everyone knows, it is virtually impossible to draw a perfect circle freehand. The senses of vision and touch are not sufficient guides to perform this operation accurately. Yet anyone who turns the handle of a pencil sharpener or an eggbeater describes a true circle in the air with every turn. The handle provides the guide, and the sense that is called into play in the kinesthetic one -- the sensing of forces and positions by the body's skeletal and muscular system Figs. 4A-4D.

It follows, then, that one of the main requirements for a CAM manipulator is that it must be equipped with a kinesthetic sense corresponding to the human one. It must be capable of detecting large or small changes of force and position, and transmitting this information accurately to the human operator.

Manipulator System Design - The second problem area is the design of the mechanical system. The following factors must be considered:

1. Equipment must be practical in terms of size, cost, reliability, and ruggedness.
2. Power and control components must suit the particular system application.
3. Good force and position sensors must be incorporated.
4. Mechanical arm kinematics must be appropriate and adequate.

The magnificently articulate human hand has 22 deg of freedom. To achieve this degree of dexterity in a practical mechanical system is impossible. The best choice of kinematics for the arm and hand is a tradeoff between effective and ideal dexterity.

In our Euclidean world it takes 6 deg of freedom of motion to position an object: 3 deg to place it in space (as defined by the three familiar coordinates x, y, and z) and 3 deg to orient the object itself (in the attitudes known as pitch, roll, and yaw). A machine can easily be designed to carry out the various necessary movements, but if a system of levers, switches, or buttons is used to control these motions, the human operator must operate the machine in a step-by-step fashion. A man cannot accurately operate more than one, or at most two, such controls at a time. It is clear, therefore, that an ideal manipulator must be coupled to the operator more directly than through levers or buttons.

Six well-related motions are needed for complete freedom to position an object. Motions required of the mechan-

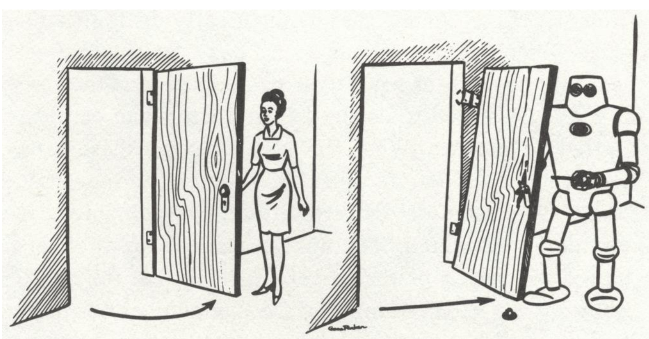

Fig. 4A - Lacking human sensing, robot snaps door

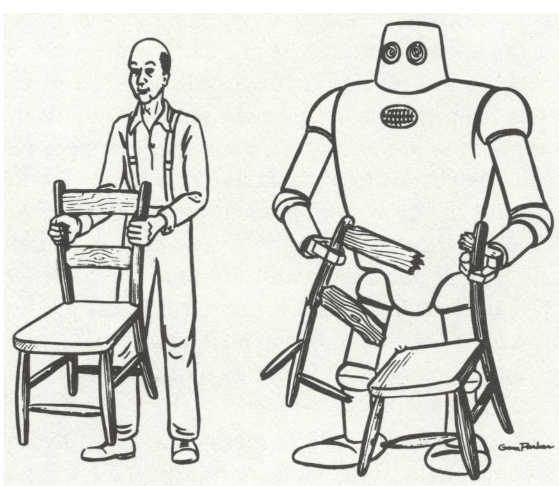

Fig. 4B - Lacking human sensing, robot shatters chair

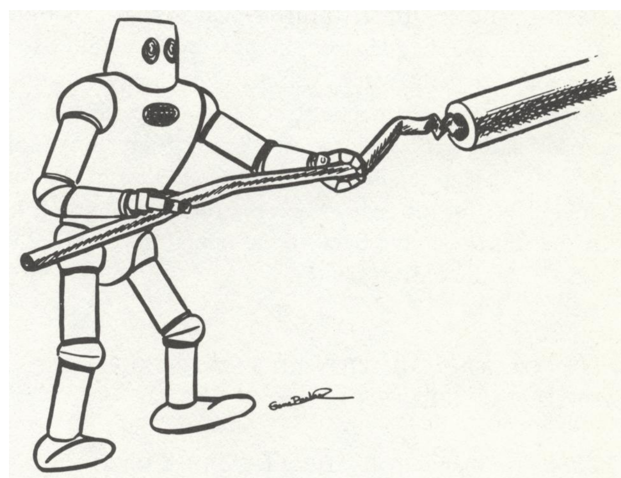

Fig. 4C - Lacking human sensing, robot jams and shatters pipe

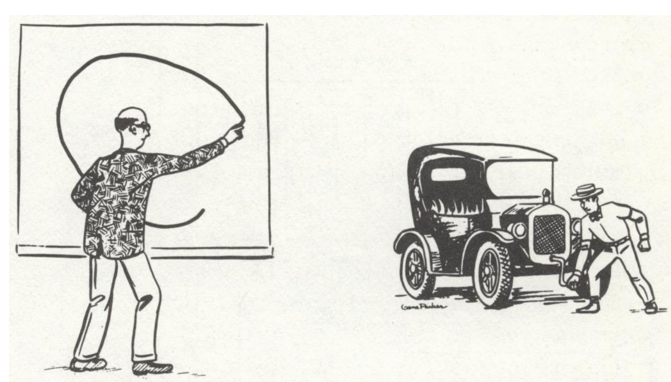

Fig. 4D - Crank handle forces perfect circular pattern ical hand depend on the tasks to be done. Specialized hands are the answer to duplicating the complex ability of the human hand. The motions must be designed to allow spatial correspondence between the operator's hand and the end effector or mechanical hand. The manipulator size can be varied while the controller is kept the size of a man. However, the topological relations between the machine and the operator must be kept the same; otherwise he would lose mental contact with the mechanical arms. The value of mimicking the operator's behavior would be lost. Spatial correspondence in force and position must be maintained.

HANDYMAN EXPERIENCE -- HUMAN FACTORS

Experience with Handyman has also revealed several critical design requirements for such a machine. It must be free of any internal forces (such as friction, dead weight, or the like) that would tend to tire the operator or mask the forces he is trying to measure. The machine's information about force and position must be reflected to him firmly and crisply so that he can work at the speed he desires, maintain smooth control of the velocity of the machine's movements, and conduct those movements without overshooting or oscillation. The amount of force reflected back to the operator should be directly proportional to that experienced by the machine. In addition, the proportion should be set at a level so that the force is strong enough to be detectable over interference, but not so strong that it tires the operator when he has to work with the machine for any length of time. The design should also make the nature of the force unambiguous; for instance, when the robot hand grasps a ball, the signal coming back to the operator should tell him whether it is the ball or opposing finger tips being compressed.

CAM's FOR CONSTRUCTION AND MATERIAL-HANDLING MACHINERY

There are many applications for CAM's where the operator is not remote from the task. In these cases, a completely hydromechanical servo system is possible. The technique allows transmission of position and force information through a simple control linkage. Fig. 5 illustrates the basic concept, which is as follows.

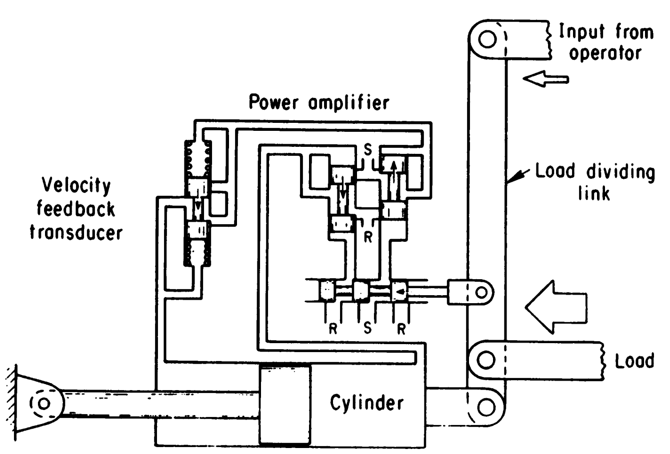

Fig. 5 - Schematic of hydromechanical servo system

The hydromechanical force-feedback system consists of hydraulic servos that are sensitive to position, velocity, and force. When at rest, servo pressure (S) (Fig. 5) is normally metered through the power amplifier values in the infinitesimal amounts needed to hold position of the cylinder. When the operator calls for a motion by moving the upper end of the load-dividing link, a three-spool valve allows servo pressure to move the power-amplifier valves in such a way that one side of the cylinder is connected to servo pressure (S), and the other is vented to return (R). As the cylinder moves to reinforce operator movement, the velocity feedback transducer prevents instability or overshoot of the desired position. The servo is bilateral where position and force information can be transmitted in both directions (from operator to task and vice versa).

This servo approach lends itself nicely to many industrial applications where the demand for simplicity and ruggedness is the unrelenting rule.

All the construction and study of CAM's to date has been related to remote applications. The human element has never been placed within, or in close proximity to the machine. Obviously, if there is no environmental restriction at the worksite, remote operation is not required and is inefficient. If the operation is mechanically difficult and is small enough, human beings with hand tools can intervene directly. Power hand tools can be added if the force and energy required to do the job is greater than can be supplied by humans. When the task is beyond these capabilities, complex powered machines are called into play. If the control requirements are difficult, deficiencies can be made up by operator training. As an example, anyone who has operated a power shovel will recollect the considerable coordination required by the human operator to perform the task of shoveling. Hand shoveling can easily be done by an untrained human using a simple, inert handtool. This simple device qualifies as a CAM!

Many construction and material-handling machines have anthropomorphous characteristics, but they are far from being CAM's and require artificial skill on the part of the operators. Nevertheless, the whole array of vehicle-mounted devices, such as power shovels, back-hoes, cranes, and stiff legs could be turned into manipulative CAM's. As presently constructed, this type of equipment uses handles, levers, wheels, pedals, switches, buttons, and a human operator. It is the lack of development of follower racks and their associated mechanical control systems that has prevented application of the anthropomorphous approach. Recent development of remote manipulators is eliminating this problem.

The Gradall boom has five motions as shown in Fig. 6 and is comparable to the human arm. Replacing the existing hand and foot control levers with a master controller would constitute simple conversion of the boom into a CAM.

This would allow a novice to become an expert boom operator in a very few minutes; he would easily be able to outperform the expert boom operator whose performance is degraded by the use of conventional control levers.

The Payloader is one of several wheel driven machines that scrapes and scoops up earth. This machine is much less anthropomorphous than the Gradall boom, but the CAM principle can be applied here to advantage also. Analysis and tests show that a 30% improvement can be realized. As currently designed, the most proficient operator gets the maximum power into the blade by continually balancing the power distribution. Maximum power is attained when the blade is neither too deep nor too shallow. Variations in available wheel traction and in the density and profile of the dirt make it very difficult to keep the blade operating consistently at maximum power. A single vertical control for the blade could greatly improve present proficiency. Such a control would be inherently provided by a CAM design. Fig. 7 describes and illustrates the concept.

A computer was used to simulate ground and earth moving machine dynamics. This was combined with a working model of the operator control, providing position and force information to the operator. Tests showed a theoretical improvement of 30% in performance. Fig. 8 shows this simulation test setup.

It is realized that there are shortcomings in the simulation, such as lack of engine loading, noise, visual cues,

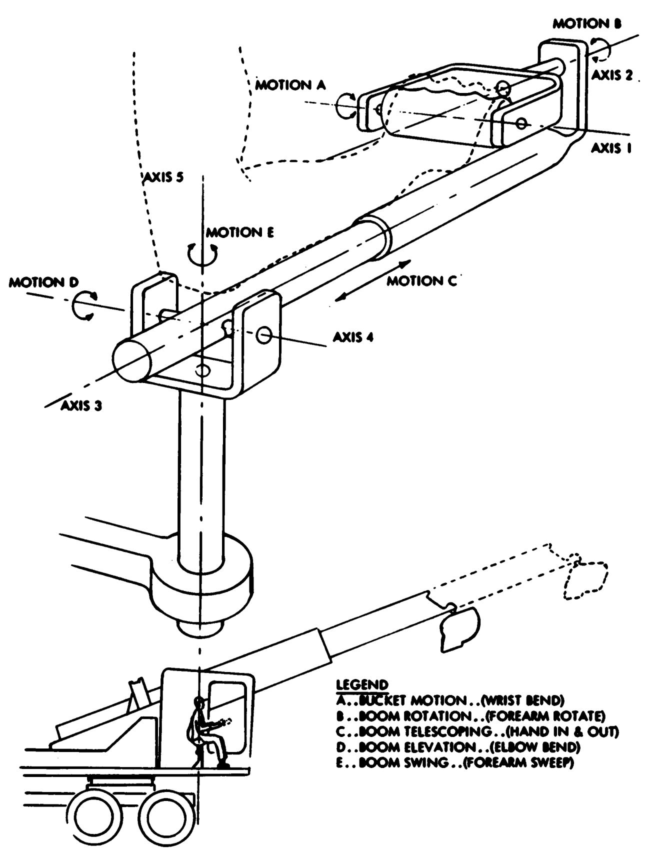

Fig. 6 - Gradall boom modified to include human force and sensing position

motion of the cab, assumed dirt density, and profile. Even so, 30% improvement with machines such as the Payloader and Gradall boom shows the potential of CAM's for special applications such as earth moving.

CAM's FOR MILITARY USE

Manipulators are presently being developed for use underwater, in space, in bomb loading and in material handling. How soon they will realize their full capability depends upon the development of system components. For instance, before the space manipulator concept can become a reality, sensor and servo components must be made compatible with the space environment, visual aids must be improved, and the data link or signal transmission system must be perfected. These are but a few of the many problems that must be solved.

Even for the straightforward application of manipulators to material handling, end effectors and servos must be perfected. Some systems have been satisfactorily built and are in use. But man is not easily satisfied; an extension of his arm must be almost faultless to adequately respond to his complex commands and preclude frustration.

<u>Walking Machines</u> - There are many military uses for walking manipulators and trucks. The General Electric Co.'s Research and Development Center is developing a walking truck and walking manipulator that will meet a number of military requirements.

The walking truck program was preceded by a balance experiment. Fig. 9 shows the equipment; spatial correspondence in force and motion is the key to control effectiveness for this mechanism. Flexing the foot determines balance action and bending at the waist causes the chassis to tilt. These two motions determine standing balance.

This equipment is the minimum necessary to provide an experimental, balance control device. The experiment demonstrates a practical system concept that involves key issues in walking machine effectiveness: namely, the use of a practical servomechanism, effective operator control methods, and easy achievement of balance and torso posture control. Human factors studies indicate that balance while standing is the most difficult part of walking dynamics.

In this particular experiment, the ability to balance is a dramatic "moment of truth." The operator's head is 15 ft above the floor. Some people refuse to try the machine because of the height. Every operator who starts to balance is apprehensive and understandably cautious. But in almost every case, the operator quickly learns that he has complete control and can balance easily and tirelessly. A few people are nervous and tense because of the height and therefore do not easily adapt to proficient control. However, complete control can be readily attained if the subject is relaxed and responds naturally to the human neuromuscular signals.

In this type of experiment, the first operator reaction is a learning process, although strictly speaking, there is very little learning. In the sense of neuromuscular training

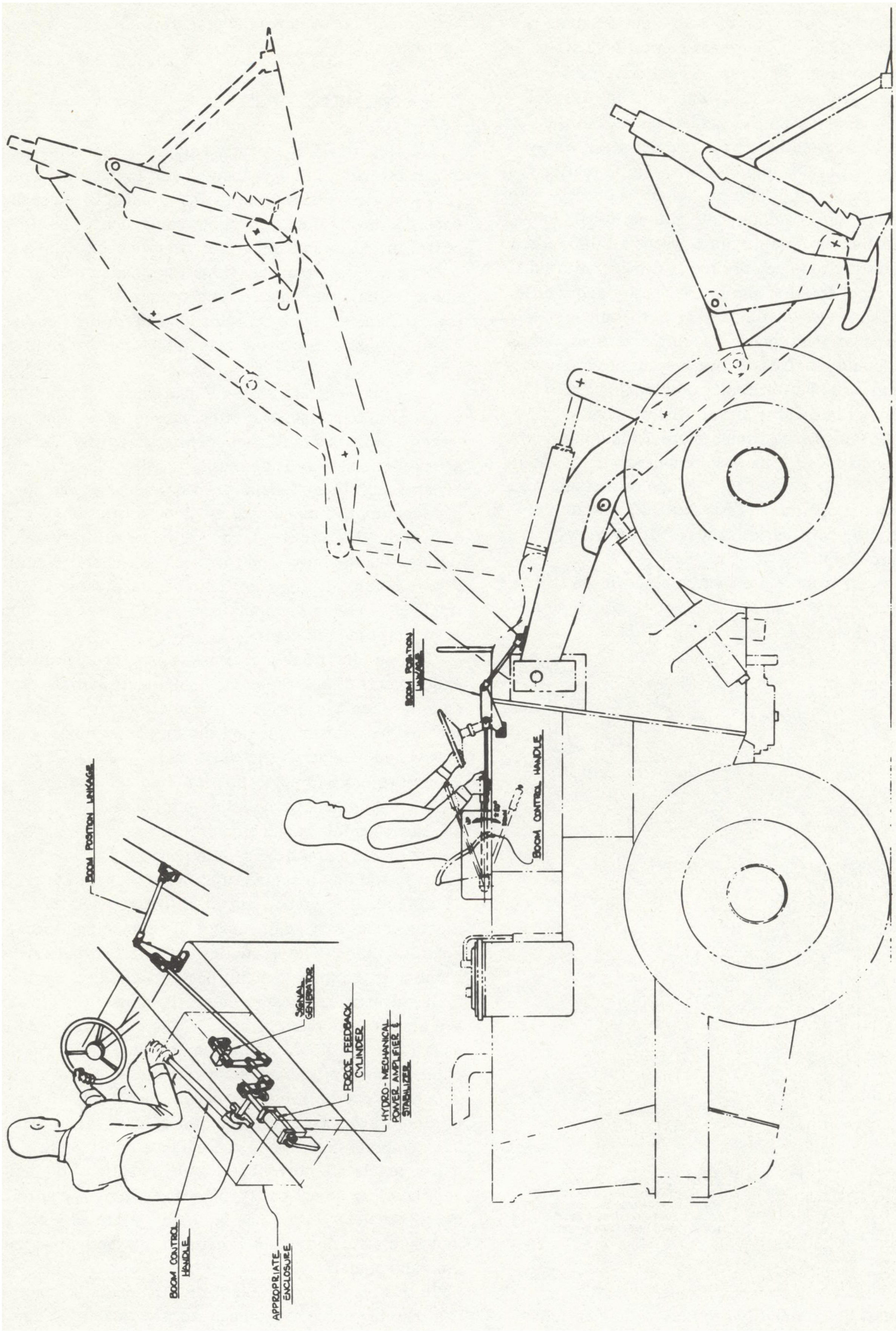

Fig. 7 - Payloader with blade power maximized through human force and position sensing

involved, the subject already "knows" how to handle the device. His learning is primarily a psychological process of overcoming strong inhibitions or preconceptions about performing such a task. Usually this change in mental attitude occurs in avalanche fashion, transforming the subject from anxious neophyte to confident "expert" in the space of a few minutes. The number of trials to reach this point varies significantly from person to person and can be strongly affected by the coaching given to the subject. Most people can muster the right attitude with their first attempt and manage to balance almost immediately; a few may require as many as a dozen attempts.

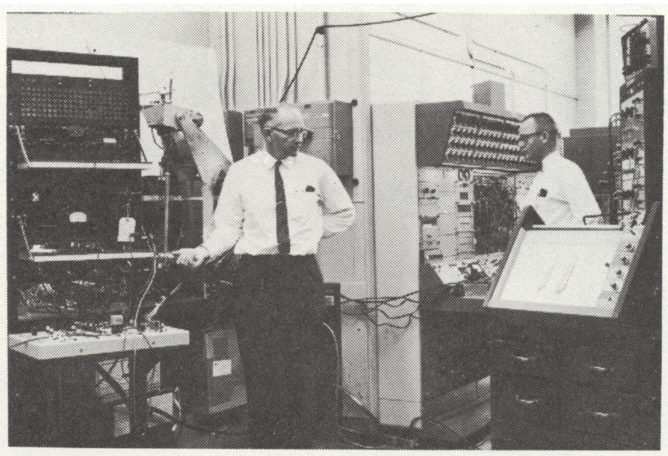

Fig. 8 - Computer simulation of human force and position sensing applied to earth-moving equipment

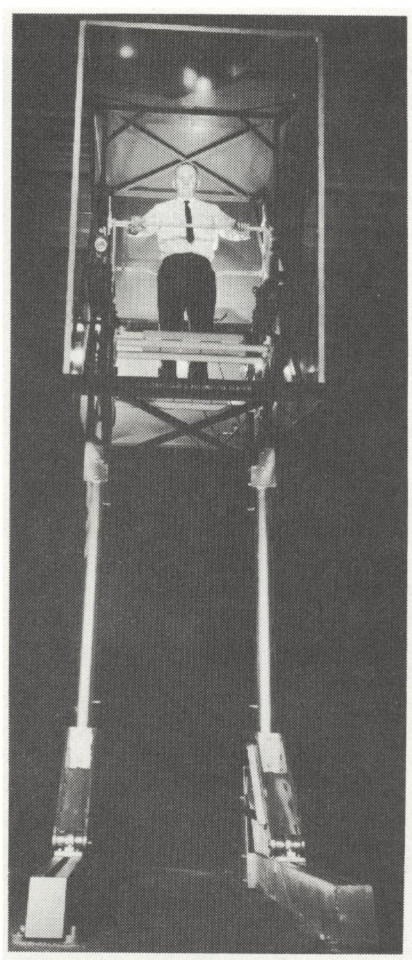

Fig. 9 - Man easily balances machine with natural force and position sensing

Upon completion of the initial tests with the balance test rig, the General Electric Co. started the design of a prototype walking machine. Further studies did not seem justified; feasibility had been established both from the mechanical design and human factors viewpoints. Fig. 10 is an industrial designer's concept of the walking truck or quadruped. However, a walking truck project, sponsored jointly by the U. S. Army and Advanced Research Projects Agency Program and Army Tank Automotive Center, is presently underway.

The front legs of the machine will be controlled by the operator's arms and the vehicle's rear legs by the operator's legs. The operator will cause the machine to move by arm and leg movements similar to those of a cross-country skier. The control arrangement will provide the means for transmitting position and force information while spatial correspondence between operator and task is maintained. The proposed quadruped will be capable of operating at a speed of approximately 5 mph, and will carry a payload of 500 lb. The proposed dimensions are: height, 10 ft; length, 12 ft; width, 3-1/2 ft.

In order to keep things in proper perspective, it must be pointed out that the walking machine is not viewed as the future means of land transportation. The vehicle cannot hope to compete with wheeled vehicles under most circumstances, even though the cost of the walking machine will be modest. However, it can most certainly compete with helicopters for high-density, high-cost, and cargo transport roles that require movement independent of weather conditions over extremely rough terrain. The walking machine will not require an expensively trained operator.

Walking machines with CAM control represent a significant breakthrough in off-road locomotion; they will permit access to a major portion of terrain too formidable for conventional vehicle forms.

Walking Manipulator - "Hardiman" is a walking manipulator that is attached to an operator like an exoskeleton. Twenty-six force reflecting servos permit the operator to lift and maneuver huge loads, while exerting only a fraction of the total force involved. Fig. 11 is a scale model of the concept being developed by the General Electric Co. Attachments to the body are at the feet, forearms, and waist. Load handling tasks such as walking, lifting, climbing, pushing, and pulling can be performed with a lift capacity of 1500 lb.

The Hardiman concept will ultimately be used for bomb loading, underwater construction, and many material handling tasks. Here again, the key to the control of Hardiman is spatial correspondence and kinesthetic force feedback. The operator will react in such a natural manner that he subconsciously considers the machine as part of himself.

Fig. 10 - Human sensing control makes the walking truck feasible

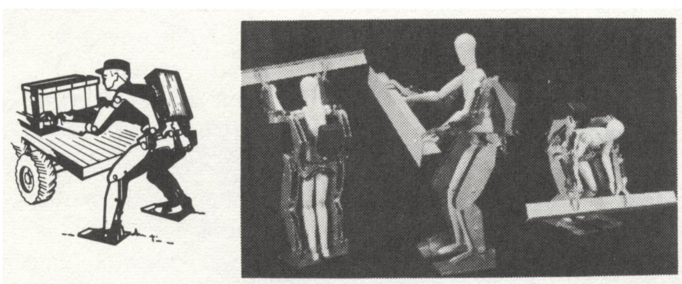

Fig. 11 - Model of Hardiman concept

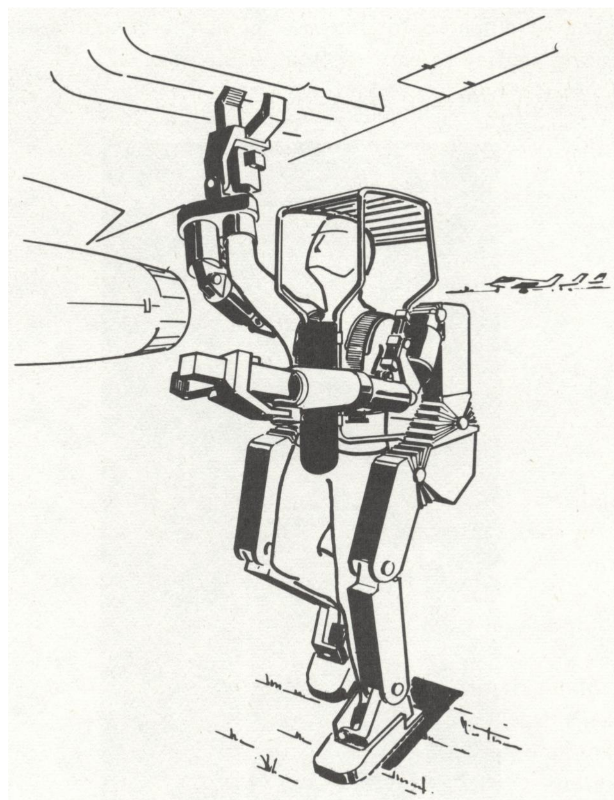

Fig. 12 - Hardiman - an exoskeletal manipulator to augment man's strength, made possible through human sensing control

Both operator and the machine can coordinate and react as an integrated system to the operator's natural neurosenses of vision, vestibular equilibrium, kinesthetic force, and proprioceptive position of body segments.

It is conceivable that a 20- or even a 50-ft tall Hardiman can be built with the operator inside as the "brain" or controller. Force and position information can be scaled down accordingly.

The General Electric Co. expects to have the prototype illustrated in Fig. 12 completed for test and evaluation in the spring of 1968. This project is sponsored jointly by the Office of Naval Research and U. S. Army Natick Laboratories.

The machine will be self-contained except for the power pack. The hydraulic servo will be driven with oil power at a pressure of 3000 psi. The feet will extend to resist any turning movement caused by picking up the load. Mechanical stops, fail-safe control, and safety crash bars will be incorporated. The hand will have prehensile gripping ability. The operator will be able to get in and out without assistance. The arms are mounted on the exoskeleton frame at the waist. They can be thought of as multiple-motion jib-cranes that are controlled at their ends by the guidance of the operator's hands. The force ratio is 25:1, so that a weight of 1500 lb will feel like 60 lb to the operator.

Fig. 13 shows an exoskeletal, unpowered leg system used to determine degree of freedom, attachments, and joint motion patterns required to do the specified tasks. Redundant or coaxial motions must be avoided to keep the operator attachment methods simple. Leg twist requirements

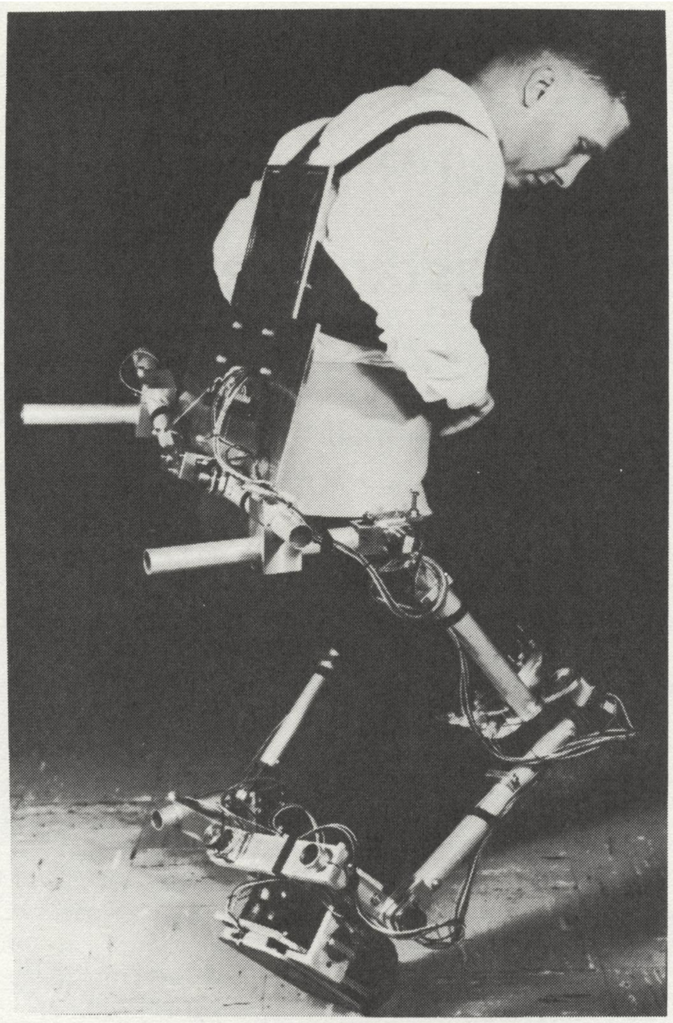

Fig. 13 - Exoskeletal kinematic study that preceded Hardiman program at General Electric Co.

can be satisfied by a controlled rotate motion in the bottom of the foot. A minimum of five motions in each leg is required.

SUMMARY

Manipulators are used for extending and augmenting man's capabilities in those instances where human judgment and control are needed. For the manipulator to be effective it must reflect information and respond to control with action that is basically consistent with the operator's natural movements. The machine and operator must coordinate and react symbiotically. The machine control must respond in a natural way to the operator's kinesthetic forces, proprioceptive position of body segments, vestibular equilibrium, and visual senses. Spatial correspondence of the controls must allow desirable reactions from the instinctive neuromuscular reflexes of the operator.

The broad implication of this control technique is that provision of position and force correspondence enables the operator to achieve a mental transference in which the machine becomes an extension of himself. No longer must the operator condition himself to the machine or learn and think about the operation involved. The man and machine become a single integrated functioning device, and the operator concentrates completely on the task to be performed.

This man-machine control is being applied in construction and material-handling industrial operations, undersea manipulators, earth-moving machinery and walking trucks. In most of these areas, developmental problems are minimal, being direct extensions of existing manipulator technology.

Military applications include space and underwater manipulators, bomb loaders, material handling, and cargo transportation over rough terrain. Industrial applications include a whole array of earth moving, logging, and material-handling operations. Ideal examples of the significant improvement possible with CAM control are the Gradall boom and the Payloader.

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