

## Dynamics and Control of Human-Robot Interaction

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### ABSTRACT<sup>1</sup>

A human's ability to perform physical tasks is limited by physical strength, not by intelligence. We have used the word "extenders" as a class of robot manipulators worn by humans to augment human mechanical strength, while the wearer's intellect remains the central control system for manipulating the extender. Our research objective is to determine the ground rules for the control of robotic systems worn by humans through the design, construction, and control of several prototype experimental direct-drive/non-direct-drive multi-degree-of-freedom hydraulic/electric extenders. The design of extenders is different from the design of conventional robots because the extender interfaces with the human on a physical level. The work discussed in this article involves the dynamics and control of a prototype hydraulic six-degree-of-freedom extender. This extender's architecture is a direct drive system with all revolute joints. Its linkage consists of two identical subsystems, the arm and the hand, each having three degrees of freedom. Two sets of force sensors measure the forces imposed on the extender by the human and by the environment (i.e., the load). The extender's compliances in response to such contact forces were designed by selecting appropriate force compensators. A mathematical expression for the extender performance was determined to quantify the force augmentation.

### 1. INTRODUCTION

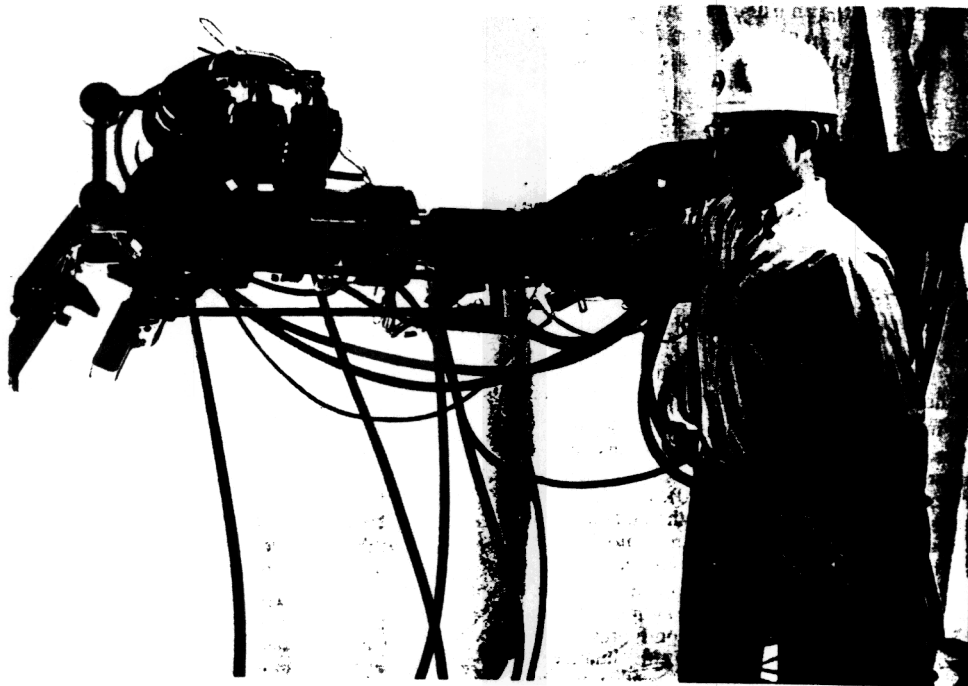
Robot manipulators perform tasks which would otherwise be performed by humans. However, in even the simplest of tasks, robot manipulators fail to achieve performance comparable to the human performance which is possible with the human intellect. For example, humans excel at avoiding obstacles, assembling complex parts, and handling fragile objects. No manipulator can approach the speed and accuracy with which humans execute these tasks. But manipulators can exceed human ability in one area: strength. The ability of a human to lift heavy objects depends upon muscular strength. The ability of a robot manipulator to lift heavy objects depends upon the available actuator torques: a relatively small hydraulic actuator can supply a large torque. In contrast, the muscular strength of the average human is quite limited. To benefit from the strength advantage of robot manipulators and the intellectual advantage of humans, a new class of manipulators called "extenders" were studied [10, 11]. The human provides an intelligent control system for the extender, while the extender's actuators provide most of the strength necessary for performing the task.

Figure 1 shows the one of our experimental hydraulic extenders designed and built at the University of California at Berkeley. The key to this new concept is the exchange of both information signals and physical power. Traditionally, the exchange of information signals only has characterized human-machine interaction in active systems. But the extender is distinguished from conventional master-slave systems in an important way: the extender is worn on the human body for the purpose of direct transfer of power. So the human body exchanges both information signals and physical power with the extender [11]. There is actual physical contact between the extender and the human body. Because of this unique interface, the human becomes an integral part of the extender and "feels" the load that the extender is carrying. In contrast, in a conventional master-slave system (i.e., when there is no force reflection), the human operator may be either at a remote location or close to the slave manipulator, but the human is not in direct physical contact with the slave. The human can exchange information signals with the slave, but not mechanical power. So the input signal to the slave is derived from a difference in the control variables (i.e., position and/or velocity) between the master and the slave, but not from any set of contact forces.

In the extender system, the input signal to the extender is derived from the set of contact forces between the extender and the human. These contact forces are part of the physical force needed to move objects, and additionally are used to generate information signals for controlling the extender. In a typical master-slave system, such natural force reflection does not occur because the human and the slave manipulator are not in direct physical contact. Instead, a separate set of actuators are required on the master to reflect forces felt by the slave back to the human operator. Force reflection occurs naturally in the extender. Without a separate set of actuators the human arm feels the actual forces on the extender, both direction of motion and a scaled-down version of mass. For example, if an extender manipulates a 200 lbf object, the human may feel 10 lbf while the extender supports the rest of the load. The 10 lbf contact forces are used not only for manipulation of the object, but also for generating the appropriate signals to the extender controller. The contact forces between the human and the extender, and the load and the extender are measured, appropriately modified via control theory to satisfy performance and stability criteria, and used as an input to the extender controller.

The objective of this research effort is to determine the rules for the control of robotic systems worn by humans through the design, construction, and control of a prototype experimental extender. Section 2 gives an overall view of the systems dynamic behavior. Section 3 and 4 discuss the control system architecture. Section 5 presents experimental results pertaining to the stability and performance of this experimental extender.

<sup>1</sup> This paper is a summary of the reference 9. Other works on Robotic Systems Worn by Humans can be found in References 2, 5, 6, 7, 13, 14 and 15.



*Figure 1: Experimental Six-Degree-of-Freedom Hydraulic Extender.*

*The extender is not a master-slave system (i.e. it does not consist of two overlapping exoskeletons.) There is no joystick or other device for information transfer. Instead, the human operator's commands to the extender are taken directly from the interaction force between the human and the extender. This interaction force also helps the extender manipulate objects physically. In other words, information signals and power transfer simultaneously between the human and the extender.*

## 2. MODELING

This section models the dynamic behaviors of the extender, the human arm and the load being maneuvered; these models are combined in Figure 2. It is assumed that the extender primarily has a closed-loop position controller, which is called the *primary stabilizing controller*. The resulting closed-loop system is called the *primary closed-loop system*. The design of the primary stabilizing controller must consider the following three issues.

- 1) Exact dynamic models for the extender are difficult to produce because of uncertainties in the dynamics of the extender actuators, transmissions and structure. These uncertainties become a major barrier to the achievement of the desired extender performance, especially when human dynamics are coupled with the extender dynamics in actual machine maneuvers. The extender's primary stabilizing controller minimizes the uncertainties in the extender dynamics and creates a more definite and linear dynamic model for the extender. Therefore, it is assumed that the dynamics of the extender are linearized by the primary stabilizing controller over a range of operation. This linear model may then be used to design other controllers that operate on forces  $f_h$  (i.e., the human force) and  $f_e$  (i.e., the load force). For the experimental extender employed in this research effort, the computed-torque method along with a PD controller [1] is used as the primary stabilizing controller to create a more definite and linear dynamics for the extender.
- 2) Extender stability must be guaranteed when the human is not maneuvering the extender. This is a very important safety feature: when the human separates his/her hand from the extender in emergency situations, the primary stabilizing controller must hold the extender stationary at the configuration at which the human arm separated from the extender.
- 3) The design of the primary stabilizing controller must let the designer deal with the effect of the extender uncertainties without concern for the dynamics of the human operator. The human arm dynamics, unlike the extender dynamics, change significantly with each human and also within one person over time [8]. Considering the control difficulties arising from the human and load nonlinear dynamics, it is a practical matter to make every effort in developing a linear dynamic behavior for the extender.

The selection of the primary stabilizing controller is not discussed here; a variety of controllers may be used to stabilize the extender in the presence of uncertainties and nonlinearities. These controllers result in uncoupled and linearized-closed-loop behavior for the extender within a certain frequency range.

Regardless of the type of primary stabilizing controller, the extender position,  $p$ , results from two inputs: 1) the desired position command,  $p_{des}$ , and 2) the forces imposed on the extender. The transfer function matrix  $G$  represents the primary closed-loop

position system which maps  $p_{des}$  to the extender position,  $p$ . Two forces are imposed on the extender:  $f_h$  is imposed by the human, and  $f_e$  is imposed by the load.  $S_h$ , an extender sensitivity transfer function, maps the human force,  $f_h$ , onto the extender position,  $p$ . Similarly,  $S_e$ , an extender sensitivity transfer function, maps the load force,  $f_e$ , onto the extender position,  $p$ . If the primary stabilizing controller is designed so that  $S_h$  and  $S_e$  are small, the extender has only a small response to the imposed forces  $f_h$  and  $f_e$ . A high-gain controller in the primary stabilizing controller results in small  $S_h$  and  $S_e$  and consequently a small extender response to  $f_h$  and  $f_e$ . Using  $G$ ,  $S_e$  and  $S_h$ , equation 1 represents the dynamic behavior of the extender.

$$p = G p_{des} + S_h f_h + S_e f_e \quad (1)$$

The middle part of the block diagram in Figure 2 represents the extender model (i.e., equation 1) interacting with the human and the load. The upper left part of the block diagram represents the human dynamics. The human arm's force on the extender,  $f_h$ , is a function of both the human muscle forces,  $u_h$ , and the position of the extender,  $p$ . Thus, the extender's motion may be considered to be a position disturbance occurring on the force-controlled human arm. If the extender is stationary (i.e.,  $p = 0$ ), then the force imposed on the extender is solely a function of the human muscle force command produced by the central nervous system. Conversely, if the extender is in motion and  $u_h = 0$ , then the force imposed on the extender is solely a function of the human arm impedance,  $H(p)$ .  $H$  is a nonlinear operator representing the human arm impedance as a function of the human arm configuration;  $H$  is determined primarily by the physical properties of the human arm [3, 12, 16]. Based on the above, equation 2 represents a dynamic model of the human arm.

$$f_h = u_h - H(p) \quad (2)$$

The specific form of  $u_h$  is not known other than it results from human muscle force on the extender. A simple study of how the central nervous system generates the desired force command  $u_h$  is given in [4]. The experimental procedure to measure  $H$  from various subjects is given in Section 6.

It is assumed that the extender is maneuvering a load. The load force impedes the extender motion. The extender controller translates the two measured interaction forces (i.e., the human forces and load forces) into a motion command for the extender to create a desired relationship between the human forces and the load forces.  $E$  is a nonlinear operator representing the load dynamics.  $f_{ext}$  is the equivalent of all the external forces imposed on the load which do not depend on  $p$  and other system variables. Equation 3 provides a general expression for the force imposed on the extender,  $f_e$ , as a function of  $p$ .

$$f_e = -E(p) + f_{ext} \quad (3)$$

In the example of accelerating a point mass  $m$  along a horizontal line, the load force,  $f_e$ , can be characterized by  $f_e = ms^2 p$ . In this case  $E = ms^2$  and  $f_{ext} = 0$  where  $p$  is the mass position and  $s$  is the Laplace operator. If the load is large and cannot be represented by a point mass, then  $E$  can be calculated using Lagrangian formulation. The diagram of Figure 2 includes two linear controllers,  $\alpha(s)$  and  $K(s)$ , which modulate the forces  $f_h$  and  $f_e$ .  $\alpha$  and  $K$  (which are implemented on a computer) must be designed to produce a desired performance in the extender system; this is described in the next section. As the Figure 2 block diagram shows, the performance filter  $\alpha$  lets designers choose the appropriate performance for the extender, and the stability filter  $K$  (which operates on both  $f_h$  and  $f_e$ ) guarantees the system stability when the extender is used by people with various arm impedances (strengths).

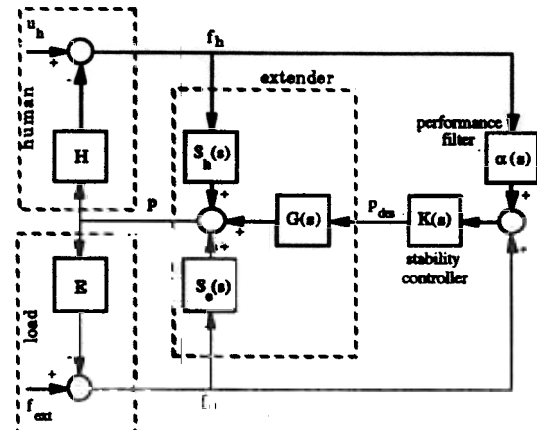


Figure 2: The overall block diagram for the extender. The extender dynamics, which are linearized by the primary stabilizing controller, are represented by  $G$ ,  $S_h$  and  $S_e$ . The human and the load dynamics are represented by two nonlinear operators  $H$  and  $E$ . Two linear controllers ( $\alpha$  and  $K$ ) modulate the forces  $f_h$  and  $f_e$ .

### 3. CONTROL

To understand the role of controllers  $\alpha$  and  $K$ , assume for a moment that neither controller is included in the system. If the commanded position,  $p_{des}$ , the human muscle forces,  $u_h$ , and the external forces,  $f_{ext}$ , all equal zero, then the extender position,  $p$ , equals zero, and no motion is transmitted to the load. This is the case when the human is holding the extender without intending to maneuver it. If the human decides to initiate a maneuver, then  $u_h$  takes on a nonzero value, and an extender motion develops from  $f_h$ . The resulting motion is small if  $S_h$  is small. In other words, the human may not have enough strength to overcome the extender's primary closed-loop controller.

To increase the human's effective strength, the extender's effective sensitivity to  $f_h$  must be increased by measuring the human force,  $f_h$ , and passing it through the controllers  $\alpha$  and  $K$ . Figure 2 shows that  $GK\alpha$ , parallel with  $S_h$ , increases the effective sensitivity of the extender to  $f_h$ . To retain a sense of the load in the extender operation, the load force,  $f_e$ , is also measured and passed through  $K$ . This produces the loop  $GK$ , parallel with  $S_e$ , which increases the effective sensitivity of the extender to  $f_e$ . The output of  $K$  is applied to the extender as a desired position command,  $p_{des}$ .  $K$  and  $\alpha$  must be chosen to ensure the stability and performance of the closed-loop extender system. The proper choice of  $K$  and  $\alpha$  achieves a desired ratio of human force to load force, and guarantees the closed-loop stability of Figure 2<sup>2</sup>. Note that both the human force,  $f_h$ , and load force,  $f_e$ , are measured for feedback to the extender: the measure of  $f_h$  (after passing through  $\alpha$  and  $K$ ) will move the extender, while  $f_e$  (after passing through  $K$ ) will impede the extender motion.

Next, the following question is addressed: how should the extender perform in a particular maneuver? In specifying the extender's performance, the designers decree the important criteria which must be met for the successful completion of a maneuver. Also in the performance specification, the designers describe the extender behavior they find desirable if stability can be maintained. Performance goals and stability requirements do conflict. As is clarified in the next section, the designers must balance this trade-off

2 Another way of interpreting  $K$  and  $\alpha$  is as follows.  $K$  is a linear controller that serves the difference between  $(f_e)$  and  $(\alpha f_h)$  to zero.

to develop an extender that both performs well and is guaranteed to be stable.

The following example illustrates a simple specification for the extender performance. The human uses the extender to maneuver a free mass in space. A reasonable performance specification for this example would state the level of amplification of the human force which is applied to the free mass. If the force amplification is large, a small force applied by the human results in a large force being applied to the free mass. If the amplification is small, a small force applied by the human results in a small force being applied to the free mass. Consequently, if the amplification is large, the human "feels" only a small percentage of the interaction force with the free mass. Most importantly, the human still retains a sensation of the dynamic characteristics of the free mass, yet the load essentially "feels" lighter.

With these heuristic ideas of system performance, the extender performance is captured in equation 4 where  $f_h^*$  is the human force applied to maneuver the extender when no load is present.  $R$  is the performance matrix, and  $[0, \omega_p]$  is the frequency range of the human arm motion.

$$(f_h - f_h^*) = -R f_e \quad \text{for all } \omega \in [0, \omega_p] \quad (4)$$

Equality 4 guarantees that  $(f_h - f_h^*)$ , the portion of the human force that is actually applied to maneuver the load, is proportional to the load force,  $f_e$ . The performance matrix  $R$  is an  $n \times n$  linear transfer function matrix. Suppose  $R$  is chosen as a diagonal matrix with all members having magnitudes smaller than unity over some bounded frequency range,  $[0, \omega_p]$ . Then the human force is smaller than the load force by a factor of  $R$ . Suppose  $R$  is chosen as a diagonal matrix with all members having magnitudes greater than unity. Then the human force is larger than the load force by a factor of  $R$ . In a more complex example, the transfer function matrix  $R$  may be selected to represent linear passive dynamic systems (i.e., combinations of dampers, springs and masses). The frequency range  $[0, \omega_p]$ , implies the desired frequency range in which the designers wish to operate the extender (i.e. human motion). Specifying  $\omega_p$  allows the designers to achieve equality 4 only for a bounded frequency range; there is no need to achieve equation 4 for an infinite bandwidth. Establishing the set of performance specifications described by equation 4 gives designers a chance to express what they wish to have happen during a maneuver. Note that equation 4 does not imply any choice of control technique for the extender. We have not even said how one might achieve the above performance specification. Equation 4 only allows designers to translate their objectives into a form that is meaningful from the standpoint of control theory.

By inspecting Figure 2, the extender position is written as a function of  $f_h$  and  $f_e$ .

$$p = (G K \alpha + S_h) f_h + (G K + S_e) f_e \quad (5)$$

Now suppose that the human maneuvers the extender through the same trajectory indicated by  $p$  in equation 5 except without any load. The no-load human force,  $f_h^*$ , is then obtained by inspection of Figure 2 where  $E = 0$  and  $f_{ext} = 0$ :

$$p = (G K \alpha + S_h) f_h^* \quad (6)$$

Equating the trajectories from 5 and 6 results in equation 7.

$$(f_h - f_h^*) = - (G K \alpha + S_h)^{-1} (G K + S_e) f_e \quad (7)$$

Comparing equations 4 and 7 shows that to guarantee the performance represented by  $R$  in equation 4, inequality 8 must be satisfied.

$$\sigma_{\max} [ (G K \alpha + S_h)^{-1} (G K + S_e) - R ] < \epsilon \quad \text{for all } \omega \in [0, \omega_p] \quad (8)$$

$\sigma_{\max}$  represents the maximum singular value.  $\epsilon$  represents a small positive number chosen by the designer to denote the degree of precision required for the specified performance within the frequencies  $[0, \omega_p]$ . A small value for  $\epsilon$  (e.g., 0.01) indicates a close proximity of the actual system performance to the specified performance  $R$  (e.g., within a 1% error). Note that the human and load dynamics,  $H$  and  $E$ , are absent from inequality 8. Thus, achievement of the specified performance  $R$  depends only on the extender dynamic behavior ( $G, S_e, S_h$ ) and on the controllers ( $K, \alpha$ ), and not on the particular human operator and load. However the stability of the closed-loop system in Figure 2 which depends on  $E$  and  $H$  must be guaranteed.

Satisfaction of inequality 8 guarantees that the performance defined by equation 4 is achieved with precision  $\epsilon$ . Therefore, the goal is to select  $K$  and  $\alpha$  so condition 8 is satisfied. Assuming that  $R$  is selected so  $R^{-1}$  always exists,  $\alpha$  is chosen to be equal to  $R^{-1}$ . (This unexpected choice for  $\alpha$  results from investigations of several design methods). Substituting  $R^{-1}$  for  $\alpha$  in inequality 8 shows that any  $K$  which satisfies inequality 9 also satisfies inequality 8.

$$\sigma_{\max} (GK) > \frac{\sigma_{\max} (S_e - S_h R) \sigma_{\max} (R)}{\epsilon} \quad \text{for all } \omega \in [0, \omega_p] \quad (9)$$

Inequality 9 suggests that, since  $\epsilon$  is a small number, the designer must choose  $K$  to be a transfer function matrix with large magnitude to satisfy inequality 9 for frequencies  $\omega \in [0, \omega_p]$  and for a given  $\epsilon, R, S_h$  and  $S_e$ . The smaller  $\epsilon$  is chosen to be, the larger  $K$  must be to achieve the desired performance.  $K$  may not be arbitrarily very large: the choice of  $K$  must also guarantee the closed-loop stability of the system shown in Figure 2, as discussed in the next section.

#### 4. STABILITY

It has been shown that, to achieve the system performance indicated by  $R$ ,  $\alpha$  must be equal to  $R^{-1}$  and  $K$  must be a large transfer function matrix satisfying inequality 9. However, the designers must realize that the closed-loop system of Figure 2 must remain stable for these choices of  $\alpha$  and  $K$ . The selection of  $K$  is particularly important since  $H$  and  $E$  generally contain nonlinear dynamic components. For example, the human arm impedance  $H$  changes from person to person and also within one person over time. The load dynamics  $E$  is also a nonlinear element as discussed earlier. Compared to the human arm and load dynamics, the extender dynamics ( $G, S_e, S_h$ ) are generally well-defined due to the primary stabilizing controller. Consequently, this analysis focuses on designing a stabilizing controller  $K$  in the presence of all bounded variations of the nonlinear operators  $H$  and  $E$  with  $G, S_e$  and  $S_h$  being known and linear dynamics. Reference 9 illuminates our approach to the design of  $K$ .

#### 5. EXPERIMENTAL ANALYSIS

The prototype six-degree-of-freedom hydraulic extender (Figure 1) is used to verify experimentally the theoretical predictions of the extender's stability and performance. The primary functions of the extender shown in Figure 1 are grasping and manipulating heavy objects. The prototype hydraulic extender's hand linkage performs the grasping function while the arm mechanism executes the load manipulations. The arm mechanism (shown in Figure 6) consists of a forearm and an upper arm and has three degrees of freedom. The rotational axes of the extender arm are designed to coincide with those of the human arm joints. Both the upper arm and the forearm are planar four-bar linkages. The materials and the

dimensions of the extender components are chosen to preserve the structural-dynamic integrity of the extender. Each link is machined as one solid piece rather than as an assembly of smaller parts. The links are made of high strength 7075 aluminum alloy to reduce the weight of the extender.

The experimental extender is capable of lifting of objects up to 500 lb when the supply pressure is set at 3000 psi. Since the high frequency maneuvers of 500 lb load is rather unsafe, the experimental analysis on the extender dynamic behavior was carried out at low level of force amplification. In order to observe the system dynamics within the extender bandwidth, in particular the extender instability, the supply pressure was decreased to 800 psi and low force amplification ratios were chosen for analysis. This allows us to maneuver the extender within 2 Hz. Matrix R in equation 21 is chosen as the performance matrix in the Cartesian coordinate frame.

$$R^{-1} = \alpha = \begin{Bmatrix} 5 & 0 \\ 0 & 7 \end{Bmatrix} \quad \text{for all } \omega \in [0, \omega_p] \quad (10)$$

The above performance specification has force amplifications of 7 times in the y-direction and 5 times in the x-direction. The human operator maneuvers the extender irregularly (i.e., randomly). Figure 3 and 4 show  $f_e$  versus  $(f_h - f_h^*)$  along the x and y directions where the slope of -5 represents the force amplification by a factor of 5.

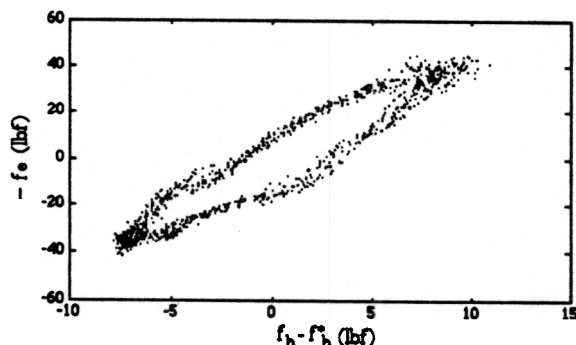


Figure 3: Load force versus human force along the x direction. Slope is approximately 5.

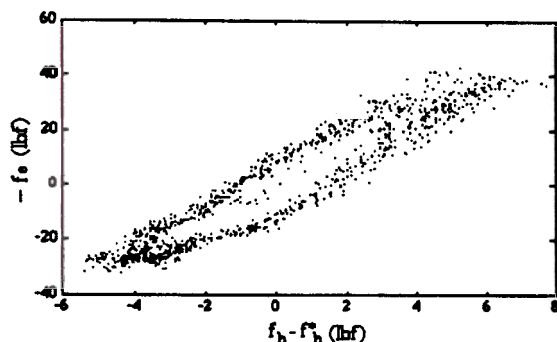


Figure 4: Load force versus human force along the y direction. Slope is approximately 7.

## 6. SUMMARY AND CONCLUSION

This article describes the dynamics of human machine interaction in robotic systems worn by humans. These robots are referred to as extenders and amplify the strength of the human operator, while utilizing the intelligence of the operator to spontaneously generate the command signal to the system. Extenders augment human physical strength. System performance is defined as a linear relationship between the human force and the load force. A six-degree-of-freedom extender has been built for experimental verification of the analysis.

## 7. REFERENCES

1. An, Chae H., Atkeson, Christopher G., Hollerbach, John M., "Model-Based Control of Robot Manipulator", MIT Press, 1988.
2. Clark, D.C. et al., "Exploratory Investigation of the Man-Amplifier Concept", U.S. Air Force AMRL-TDR-62-89, AD-390070, August 1962.
3. Cooke, J. D., "Dependence of human arm movements in limb mechanical properties", Brain Res., Volume 165, pp: 366-369, 1979.
4. Cooke, J. D., "The Organization of Simple, Skilled Movements", Tutorials in Motor Behavior, edited by G. Stelmach and J. Requin, Amsterdam, Elsevier, 1980.
5. GE Company, "Exoskeleton Prototype Project, Final Report on Phase I", Report S-67-1011, Schenectady, NY, 1966.
6. GE Company, "Hardiman I Prototype Project, Special Interim Study", Report S-68-1060, Schenectady, NY, 1968.
7. Groshaw, P. F., "Hardiman I Arm Test, Hardiman I Prototype", Report S-70-1019, GE Company, Schenectady, NY, 1969.
8. Houk, J. C., "Neural control of muscle length and tension", in: Motor control, ed. V. B. Brooks. Bethesda, MD, American Physiological Society Handbook of Physiology.
9. Kazerooni, H., Guo, J., "Extender: A Case Study for Human-Robot Interaction via the Transfer of Power and Information Signals", ASME Journal of Dynamic Systems, Measurement, and Control. Vol. 115, No. 2, June 1993.
10. Kazerooni, H., "Human-Robot Interaction via the Transfer of Power and Information Signals", IEEE Transactions on Systems and Cybernetics, Vol. 20, No. 2, Mar. 1990.
11. Kazerooni, H., Mahoney, S., "Dynamics and Control of Robotic Systems Worn By Humans", ASME Journal of Dynamic Systems, Measurement, and Control. Vol. 133, No. 3, September 1991.
12. Marsden, C. D., Merton, P. A., Morton, H. B., "Stretch reflexes and servo actions in a variety of human muscles", Journal of Physiol., London, Volume 259, pp: 531-560.
13. Mizzen, N. J., "Preliminary Design for the Shoulders and Arms of a Powered, Exoskeletal Structure", Cornell Aeronautical Laboratory Report VO-1692-V-4, 1965.
14. Mosher, R. S., "Force Reflecting Electrohydraulic Servomanipulator", Electro-Technology, pp. 138, Dec. 60.
15. Mosher, R. S., "Handyman to Hardiman", SAE Report 670088.
16. Stein, R. B., "What muscles variables does the nervous system control in limb movements?", J. of the behavioral and brain sciences, 1982, Volume 5, pp 535-577.