# Human Machine Interaction via the Transfer of Power and Information Signals; Part I: Fundamentals

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## ABSTRACT

Robot manipulators are designed to perform tasks which would otherwise be executed by a human operator. No manipulator can even approach the speed and accuracy with which humans execute these tasks. But manipulators have the capability to exceed human ability in one particular area; strength. Through any reasonable observation and experience, the human's ability to perform a variety of physical tasks is limited not by his[1] intelligence, but by his physical strength. If, in the appropriate environment, we can more closely integrate the mechanical power of a machine with intellectually driven human hand under the supervisory control of the human's intellect, we will then have a system which is superior to a loosely-integrated combination of a human and his fully automated robot as in the present day robotic systems. We must therefore develop a fundamental approach to the problem of this "extending" human mechanical power in certain environments. "Extenders" will be a class of robots worn by humans to increase human mechanical ability, while the wearer's intellect remains the central intelligent control system for manipulating the extender. The human body, in physical contact with the extender, exchanges <u>information signals</u> and <u>power</u> with the extender.

Commands are transferred to the extender via the contact forces between the wearer and the extender as opposed to use of joystick (master arm), push-button or key-board to execute such commands that were used in previous man amplifiers. Instead, the operator becomes an integral part of the extender while executing the task. In this unique configuration the mechanical power transfer between the human and extender occurs in addition to information signal transfer. When the wearer uses the extender to touch and manipulate an object, the extender transfers to the wearer's hand, in feedback fashion, a scaled-down value of the actual external load which the extender is manipulating. This natural feedback force on the wearer's hand allows him to "feel" the scaled-down value of the external forces in the manipulations. Extenders can be utilized to maneuver very heavy loads in factories, shipyards, airports, and construction sites. In some instances, for example, extenders can replace forklifts. Part I describes the fundamentals, and the experimental results, while Part II is devoted to the general analysis on dynamics and control .

## 1. INTRODUCTION

Manipulators have the potential to exceed human ability in one particular area, strength. The ability of a human to lift heavy objects is determined by his own muscular strength. The ability of a robot manipulator to perform the same tasks depends upon the available actuator torque. A relatively small hydraulic actuator can supply a large torque. In contrast, the muscular strength of the average human is quite limited. Extenders will be a class of robot manipulators which will extend the strength of the human arm, while maintaining human control of the task. The extender is

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[1] The pronouns "he" and "his" are used throughout this article are not meant to be gender-specific.

distinguished from conventional master-slave[2] systems; the extender is worn by the human for the purpose of direct transfer of power. Consequently, there is actual physical contact between the extender and the human, allowing transfer of mechanical power in addition to information signals[3]. Because of this unique interface, control of the extender trajectory can be accomplished without any type of joystick, keyboard, or master-slave system. The human provides an intelligent control system to the extender, while the actuators ensure most of the necessary strength to perform the task. The key point is the concept of "transmission of power and information signals". The human becomes a part of the extender, and "feels" some scaled version of the load that the extender is carrying. In contrast, in a conventional master-slave system, the human operator may be either at a remote location or close to the slave manipulator, but he is not in direct physical contact with the slave in the sense of transfer of power. Thus the operator can exchange information signals with the slave, but mechanical power is not exchanged directly. In a typical master-slave system, 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[4].

In the extender system, the input to the extender will be derived from the set of contact forces resulting from the contact between the extender and the human. This set of contact forces is being used to manipulate an object in addition to generating information signals for the extender control. Note that force reflection occurs naturally in the extender, the human arm will feel a scaled down version of the actual forces on the extender without a separate set of actuators. For example, if an extender is used to manipulate a 100 lbf object, the human may feel 10 lbf while the extender will take the rest of the load. The 10 lbf contact force is used not only for manipulation of the object, but also for generating the appropriate signals to the extender controller. In other words, the contact force between the human and the extender is measured, appropriately modified (in the sense of control theory to satisfy the performance and stability), and used as an input to the extender control, in addition to being used for actual maneuvering.

A simple example is given in Figure 1a to show some fundamental concepts about the extender. Figure 1a shows a one degree of freedom extender, moving a load. If the load weight is $W$, at equilibrium, the following equality is true for the extender. (Figure 1b)

$$f_e h = W L \tag{1}$$

where $\tau$ is the actuator torque and $f_e$ is the force imposed by the human on the extender. The goal is to develop a control algorithm in the system such that $f_e h$ is always a constant portion of $\tau$. In other words, the human always feels a scaled down version of the actual necessary force to lift the load. Suppose the load weighs 100 pounds, while $L=2'$ and $h=1'$, it is then desired to control the extender such that $f_e = 10$ lbf, for example, while $\tau = 190$ lbf.ft. Note that the 10 lbf on the extender, imposed by human, is the amount of force that is used to help lifting the load. The human will feel this 10 lbf as a reaction force (toward down in Figure 1). The human uses this force as a natural reflection to feel the scaled down version of the actual force. If the system is accelerating, the total load in lifting $W$ with acceleration of $\ddot{\theta}$ is $WL\sin(\theta) + J\ddot{\theta}$ where $J$ is the moment of the inertia of the extender and load. ($\theta$ is measured from a vertical line).

$$\tau + f_e h = WL\sin(\theta) + J\ddot{\theta} \tag{2}$$

A control algorithm must be designed such that $f_e h$ is constant and a small portion of $\tau$.

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[2] A master-slave system (tele-operator system) uses a control joystick of similar geometry to the manipulator for input. The joystick has position transducers at the joints to measure displacement, and the output from these transducers is used as an input to the manipulator. Thus the motion of the manipulator follows that of the joystick. The joystick is called the master manipulator, and the mechanical manipulator is called the slave. Ideally, the motion of the slave will be identical to that of the master [19].

[3] The human-machine interaction in active systems has been traditionally characterized by the exchange of "information signals" only. For example in human-computer interaction, the human sends information signals to the computer via a keyboard. In another example, a car driver sends an information signal to the engine by pushing the accelerator. There is no power transformation between the driver and the car; the driver does not feel the load on the car.

[4] The elimination of force feedback in remote master-slave manipulation may result in poor positioning precision and possible instability [11, 18, 25].

## 2. HISTORY AND BACKGROUND

The extender employs a direct physical contact between the human and the manipulator for the purpose of accepting power and information signals. The concept of a device to increase the strength of a human operator using a master-slave system has existed since the early 1960s. The concept was originally given the name "man-amplifier". The man amplifier was defined as a type of manipulator which has the effect of greatly increasing the strength of a human operator, while maintaining human supervisory control of the manipulator. Note that previous systems were designed based upon the master-slave concept, rather than the direct physical contact between human and manipulator for the purpose of power and information signals.
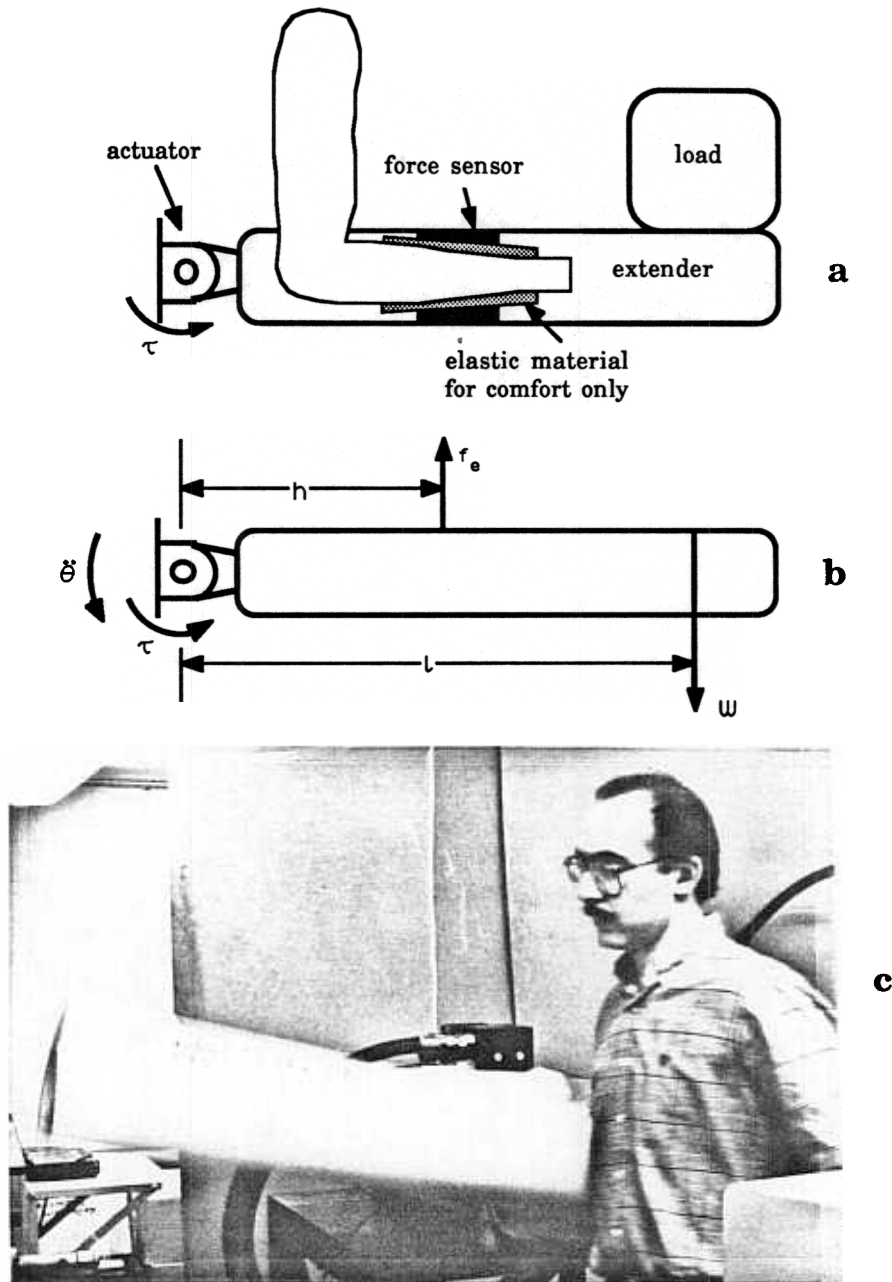


Figure 1: a: One degree of freedom (dof) experimental extender. b:The free body diagram of the extender. c: The experimental one dof extender at the Motion Control Laboratory of University of Minnesota. This experimental extender is made of steel (160 lbf) to simulate the load.

In the early 1960s, the Department of Defense was interested in developing a powered "suit of armor" to augment the lifting and carrying capabilities of soldiers. The original intent was to develop a system which would allow the human operator to walk and to manipulate very heavy objects. In 1962, research was done at the Cornell Aeronautical Laboratory for the Air Force to

determine the feasibility of developing a master-slave system to accomplish this task [4]. It was determined from this study that duplicating all human motions would not be practical, and that further experimentation would be required to determine which motions were necessary. It was also determined that the most difficult problems in designing the man amplifier were in the areas of servo, sensor and mechanical design.

The Cornell Aeronautical Laboratory did further work on the man amplifier concept [20]. It was determined that an exoskeleton[5] having far fewer degrees of freedom than the human operator would be sufficient to carry out most desired tasks. A preliminary arm and shoulder design was developed at Cornell in 1964. As a result of this preliminary design, it was determined that the physical size of the hydraulic actuators required to amplify the human operator's strength placed a limitation on the amplifying ability of the manipulator.

Further work on the man amplifier concept was carried out at General Electric from 1966 to 1971 [8-11, 17, 21 and 22]. GE carried the work through prototype development and testing. This man-amplifier, known as the Hardiman, was designed as a master-slave system. The Hardiman was a set of overlapping exoskeletons worn by the human operator. The master portion of the system was the inner exoskeleton, which moved due to the motions of the operator and served as the master for the system. The outer exoskeleton consisted of a hydraulically actuated slave which followed all the motions of the master. Since the master followed the motions of the operator, the slave exoskeleton also followed the motions of the human operator.

In contrast with the Hardiman and other man amplifiers, the extender is not a master-slave system. There is no joystick or master device for information transfer. Instead, the human operators commands to the extender are taken directly from the interaction force between the human and the extender. This interaction force is also used to help the extender manipulate an object. In other words, the power and information signals transfer simultaneously at one point. The controller developed for the extender translates the signals representing the interaction force signals into a motion command for the extender. This allows the human to initiate tracking commands to the extender in a very natural way[6].

Some of the major areas of application for the extender might include manufacturing, construction, loading and unloading aircraft, maneuvering cargo in shipyards, foundries, mining or any situation which requires precise and complex movement of heavy objects. Two main categories of manipulation have been defined for the extender: constrained and unconstrained. In unconstrained maneuvers, the extender is free to move in all directions without any interaction with another system. On a factory floor where heavy objects need to be moved about, the extender could be worn by a worker who would then have the ability to lift and carry these objects. This would be an example of unconstrained maneuvering. Currently, heavy pieces may be moved about by forklifts, pulleys, cranes or similar equipment. The extender will offer an advantage over these methods because it is designed to follow the human arm motions in a very "natural" way. The human will be able to manipulate heavy objects more easily without the use of any key board, joy stick or push button. It is expected that the human operator will be able to maneuver heavy loads with greater dexterity, speed, and precision. In comparison with existing systems such as forklifts, pulleys, and cranes, the extender offers the human the opportunity to adjust the orientation of objects. Figure 2 shows the schematic of the architecture for a prototype multi-dof extender being built at the University of Minnesota. This type of motion may be required for manipulating cargo in a shipyard, assembly tasks, or in a construction application such as installing large windows. The extender is shown without a base for clarity. In reality, the extender might be attached to a mobile or stationary base. Also note that the sleeve into which the human's arm would be inserted is eliminated in the interest of clarity.

The second category of manipulation with the extender is constrained manipulation. This type of manipulation includes any movement which requires interaction with a third object, the "environment". Examples of constrained manipulation by the extender might include operation of a pneumatic jack, bending of materials, or press fitting.

Due to the natural communication (in the sense of footnote 6) between the human and the extender, we believe there are major advantages using the extender over conventional methods of manipulating heavy objects:

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[5] Exoskeleton: An external structure in the shape of the human body.

[6] A point must be made about what we mean by "natural way". If "talking" is defined as a natural method of communication between two people, then we would like to communicate with a computer by talking rather than using a keyboard. The same is true here; if we define "maneuvering the hands" as a natural method of moving loads, then we would like to only move our hands to maneuver a load, as opposed to using any keyboard or joystick.

1) The human needs very <u>little training</u> to operate the extender as opposed to driving a system via keyboards and joysticks.

2) The human operator can <u>react quickly</u> to provide an input to the extender because the forces acting on the extender are naturally fed back. For example, the operator can orient a heavy object using the extender faster than driving a small crane via joysticks and keyboards.

3) The human operator <u>can feel</u> the scaled down effect of loads and/or interaction forces on the extender because the forces acting on the extender are naturally reflected back. A master-slave system needs two sets of actuators for force reflection on the human.

4) The operator can maneuver heavy objects much more <u>naturally</u>, for example if an object is falling, then the operator is able to prevent the falling more quickly than using a forklift or a master-slave system.
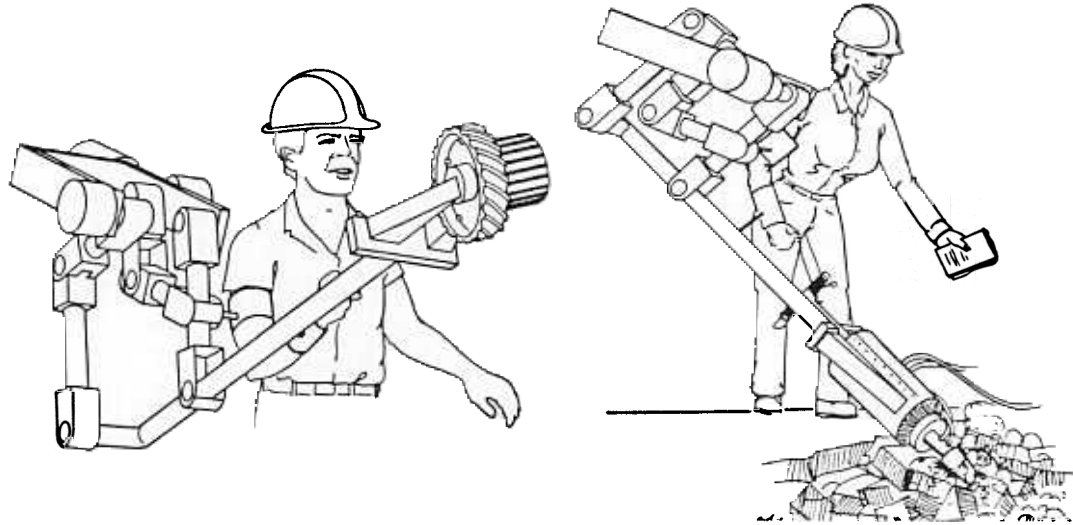


Figure 2: Extenders can be used in a manufacturing or construction environment as a fork lift.

The extender also has the potential to become a useful upper limb orthosis for the physically impaired. An orthosis is an externally applied device which improves the functionality of an impaired limb[7]. The main purpose of an orthosis is to enhance the functionality of existing body segments; in contrast with a prosthesis, which serves to replace body segments [4, 23, and 24]. The extender would be classified as an orthosis, rather than a prosthesis, because it would enhance existing motor ability instead of replacing an absent segment.

The first tests on a motor controlled orthosis attached to the upper limb were carried out in 1956 [2]. This was a myoelectric[8] system which used the electrical output of contracting muscles as a control input. The muscles which are used to voluntarily drive body segments are known as striated muscles. Whenever a striated motor unit is contracted, an electrical signal is generated as a result of the depolarization which initiates the contraction. The sum of the separate depolarizations from each motor unit in the muscle is known as an electromyographic or EMG signal. There may be cross talk from other contracting muscles in the region of interest which will interfere with the desired input. The signal obtained from the muscles is very small, and thus noise may be a serious problem. Also, considerable concentration is required to perform manipulation with more than one degree of freedom, which has a serious effect on patient acceptance of the device.

Another method of using the myoelectric signal is to generate a command based on a pattern of myoelectric signals received from the patient. For example, if the signals are accepted from 4 control sites, each combination of signals from these sites commands a different motion. A signal from site four, followed by a signal from site two, may be interpreted as a command to simultaneously raise the upper arm and extend the lower arm. A major disadvantage of this type of system is the limited number of unique combinations of control site signals.

Another alternative for command generation is the mechanical input system. Mechanical input systems rely on a joystick or some other type of input device to initiate a control command. The orthosis follows the motion of the joystick, i.e. up-down, left-right or backward-forward. A particular

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[7]Appropriate modification of the extender for this use would include decreasing the overall size of the extender, decreasing the size of the actuators used, and improving the cosmetic appearance of the extender. Recent discoveries in superconductivity may lead to design and construction of electric motors with high power to weight ratio so they can be employed to power the extender.

[8] Myoelectric: Pertaining to the electric or electromotive properties of muscle.

disadvantage of this type of system is the coupling of the motion of the joystick with that of the orthosis.

A third alternative for command generation is the photoelectric system, which converts light energy to electric energy for use as a command signal. Such a system requires a light source which can be manipulated by the patient and photo cells to convert the energy [5].

There is no orthosis currently available which, while allowing the patient to assist in driving the orthosis with his own muscles, also guarantees complete control of the body segment. Elastic devices, in contrast, may improve the functionality of the upper limb, but do not significantly enhance the lifting capability of the patient. Inelastic, externally powered devices completely override remaining functional ability. This is undesirable in cases where continued use of the arm might facilitate further recovery [6]. The extender would augment the lifting ability of the patient and also allow continued use of the patient's remaining motor ability. For a patient to employ the extender, he must have some ability to move his arm. The capability for some motion is necessary because the extender requires motion from the user in order to move. Thus, the patient must use his remaining muscle ability to drive the extender. The extender would serve to improve the patient's limb function while utilizing the remaining natural limb function. This method of improving limb function would be very useful to the patient who may recover further limb function with increased limb use. Instead of promoting muscle atrophy, the extender system could be therapeutic and promote further muscle development in the limb.

## 3. EXPERIMENTAL EXTENDER

To understand the issues in control and dynamics involved in human/machine interaction, the control of an experimental one dof extender is described (Figure 1c). The general building blocks on nonlinear dynamics and control (in particular the stability of the human and extender taken as a whole) are given in part II of this paper. Figure 3 shows the schematic of the control loop for a one dof experimental extender [1]. Two forces add up to maneuver the extender: $f_e$ and $\tau$. The contact force between the human and the extender, $f_e$, is the result of human intention to move up the extender and the actuator torque, $\tau$, is the result of the feedback. A velocity controller is chosen as the lowest level of control for the extender so the extender is stabilized independently of the human dynamic behavior[9].
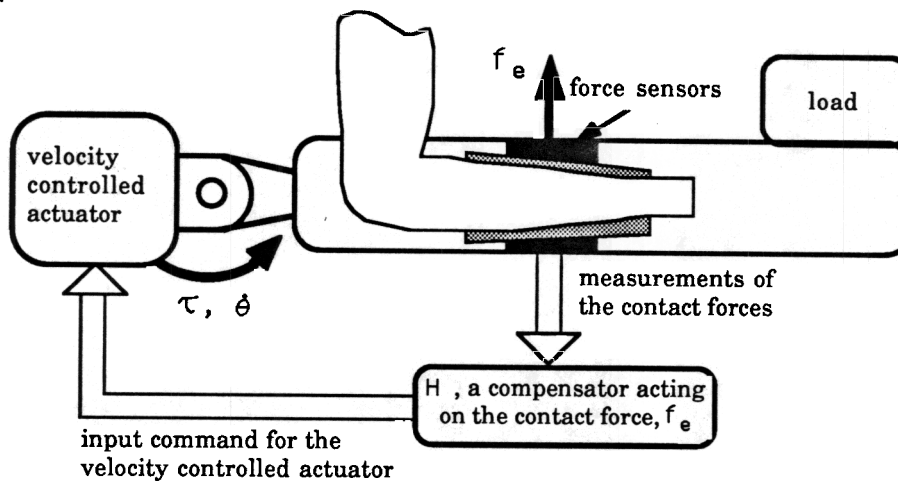


Figure 3: The schematic of the one dof extender. $f_e$ is the force imposed on the extender by the human. $\tau$ and $\dot{\theta}$ are the torque and the velocity of the extender.

The interaction force between the human and the extender is simply fed back and used (after passing through the compensator, H) as an input to the velocity controlled extender. When the human pushes against the extender, the contact force, $f_e$, is measured and passed through the compensator, H. The output of this compensator is used as the input command for the velocity controlled actuators of the extender. When the human does not push against the extender, the contact force, $f_e$, and consequently the input command to the actuator are zero. The zero command for the velocity controlled actuators results in zero speed for the extender. In other words, when there is no push from the human, the extender will be stationary. H is of paramount importance in the stability of the system of the human and the extender taken as a whole[10]. For a given load, it is desirable to have the bandwidth of the extender wide so it can keep up with the high speed motion of the human arm. It is

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[9] It is of practical importance that the extender be stable when the human is not wearing it.
[10] Similar analysis is given in references 15 and 16 to describe the stability of an *autonomous* robot interacting with an environment.

also desirable to have the contact force remain as small as possible so one can maneuver a large load with a small contact force[11]. It has been shown in part II, equation 47 , that in order to achieve a fast response and a small (but nonzero) contact force one needs large values for H. However, one cannot choose an arbitrarily large value for H; the stability of the system must also be guaranteed. Part 2 describe the instability via a formal mathematical framework. Here it is explained how instability may occur in the system when a large value for H is chosen. Suppose the compensator H has a large gain[12] over a frequency range of operation. If the human decides to move up the object, the extender will move up with such a large velocity that it pulls the human arm up. This reverses the direction of the contact force between the human and the extender (downward in Figure 3). Then the extender responds to the downward force with a large velocity which will pull down the human arm. This periodic motion occurs in a very short amount of time and the motion of the extender will become oscillatory and unbounded. H must be designed such that its gain is large enough for the human to maneuver an object with high speed while stability is guaranteed [7].

First, the dynamic behavior of the experimental 1 dof extender and its velocity controller[13] is given here. An explanation of how one additional force feedback passing through a compensator allowing for a stable interaction will follow. The prototype extender is powered by an EXCELLO SS-8-100 limited rotation hydraulic actuator ($100°$ total rotation, 1800 ft.lbf maximum torque at 3000 psi). A MOOG 72-102 2-stage servovalve has been used to drive the actuator. The servovalve has the rated flow of 40 GPM at 1000 psi, with 0.02 Amps of the input current. The dynamic behavior of a servo hydraulic actuator is governed by equations 3-5. Equation 3 is the valve dynamics while equations 4 and 5 represent the flow continuity and actuator dynamics [17].

$$Q_l = K_q \, I - K_p \, P_l \tag{3}$$

$$Q_l = \dot{\theta} \, D_m + \frac{V_t}{4\beta_e} \frac{d}{dt} P_l \tag{4}$$

$$P_l \, D_m = J \, \ddot{\theta} \tag{5}$$

where

$Q_l$ = load flow  (in$^3$/sec)
$K_q$ = flow gain  (7700 in$^3$/sec/Amp for MOOG 72-102  2-stage servovalve)
$I$  = current  to drive the servovalve
$K_p$ =  pressure gain
$P_l$ = load pressure (psi)
$\dot{\theta}$ = angular velocity  of the extender (rad/sec)
$D_m$ = actuator volumetric displacement (7.62 in$^3$/rad for EXCELLO SS-8-100)
$J$ = moment of inertia (113.6 ft.lbf.sec$^2$)
$\beta_e$ = hydraulic fluid modulus of elasticity (100,000 psi)
$V_t$ = total contained volume in actuator  (13.3 in$^3$ for EXCELLO SS-8-100)

combining equations 3-5, equation 6 will result as an open loop transfer function that maps the servovalve input current to the  extender velocity.

$$G_p(s) = \frac{\dot{\theta}}{I} = \frac{\frac{K_q}{D_m}}{\frac{s^2}{\omega_e^2} + \frac{2\zeta_e s}{\omega_e} + 1} \tag{6}$$

where $\omega_h$ and $\zeta_h$ are given by  the following equations:

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[11]The contact force should be small but non-zero. It is necessary to have non-zero contact force, so the human always feels a constant portion of the actual load.

[12] One can use the singular value for linear systems or $L_p$ norm for nonlinear systems to represent the gain.

[13] The nature of the velocity controller is not of importance in this analysis. One can always use a number of advanced nonlinear control methodologies for the development of robust velocity controllers for robotic applications [26, 27]. In the simplest case, one can design a velocity controller for each degree of freedom of the extender independently,  while satisfying the  extender closed loop stability.

$$\omega_e = \sqrt{\frac{4\beta_e D_m^2}{V_t J}} \qquad\qquad \xi_e = \frac{K_p}{D_m}\sqrt{\frac{\beta_e J}{V_t}}$$

The flow gain $K_q/D_m$ is a nonlinear function of the pressure drop across the valve, the load on the actuator, and the distance that the valve is stroked away from null. $\xi_e$ is highly nonlinear, and will increase rapidly past unity as the valve amplitude is increased. The theoretical value of $\omega_e$ is 11.8 hertz[14]. The theoretical open loop transfer function (equation 6) was then compared to experimental frequency response to find actual value for $\omega_e$, $\xi_e$ and $K_q/D_m$. Experimental verification of the actuator dynamics was performed by driving the system with a sinusoidal signal, $n_r$, and observing the velocity output from the tachometer. Figure 4 shows the block diagram of the system for experimental system identification. $n_r$ and $n_\theta$ represent the command and extender velocity in the computer.
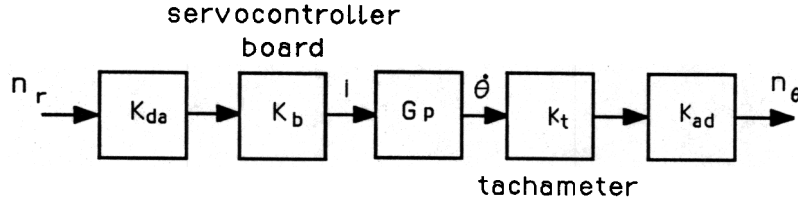


**Figure 4: Plant Identification Block Diagram.** $K_{da}$: D/A convertor gain(10 Volts / 2048) , $K_b$: Servocontroller board gain (.0077 Ampere/Volts), $K_t$: tachometer gain(.5Volts/rad/sec) , $K_{ad}$: A/D convertor gain (2048 / 1.25 Volts)

Equation 7 is the theoretical transfer function observable from the data stored in the computer.

$$\frac{n_\theta}{-} = \frac{K_{da}\, K_b\, \dfrac{K_q}{D_m}\, K_t\, K_{ad}}{\dfrac{s^2}{\omega_e^2} + \dfrac{2\zeta_e s}{\omega_e} + 1} \tag{7}$$

Figure 5 shows the experimental frequency response of the open loop system. The theoretical transfer function was shaped to fit the experimental data, resulting in a damping ratio $\xi_e = .45$, a hydraulic natural frequency $\omega_e = 8.4$ hertz, and a plant gain $K_q/D_m = 220$ rad/sec/Amp.
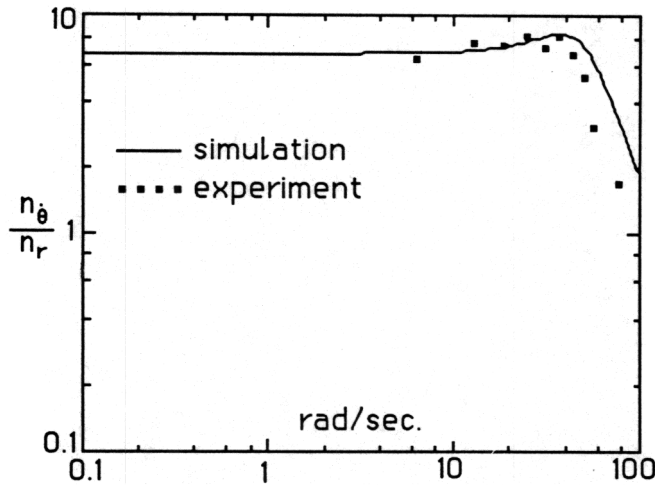


**Figure 5: Open Loop Dynamic Behavior of the Hydraulically Driven Extender**

Compensator K(s) is then designed to develop a closed loop velocity control for the extender (Figure 6). Equation 8 shows the proposed transfer function for the compensator. The integrator overcomes the friction forces and the lead compensators generate positive phase angle for the loop transfer function for stability. Proposing equation 8 for the compensator, the closed loop transfer function is given by equation 9.

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[14]This number includes Meritt's 40% reduction factor [19, page 140].
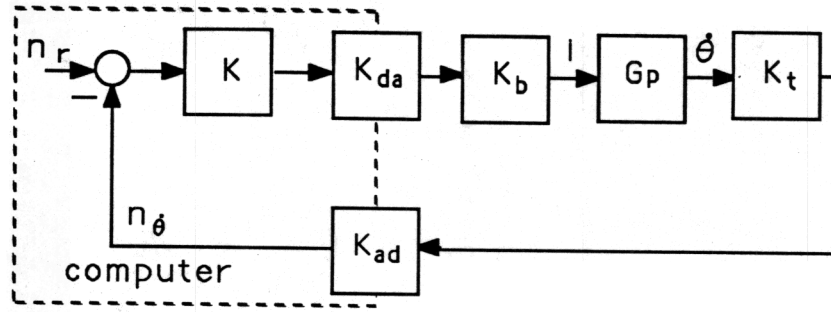
Figure 6: The Closed Loop Velocity Control. The arguments of the transfer functions have been eliminated in all the block diagrams.

$$K(s) = K_o \frac{(\frac{s}{\alpha}+1)(\frac{s}{\beta}+}{s} \qquad (8)$$

$$G_e(s) = \frac{n_\theta}{n_r} = \frac{\gamma(\frac{s}{\alpha}+1)(\frac{s}{\beta}+}{\frac{1}{\omega_e^2})s^3 + (\frac{2\zeta_e}{\omega_e}+\frac{\gamma}{\alpha\beta})s^2 + (1+\frac{\gamma}{\alpha}+\frac{\gamma}{\beta})s + \gamma} \qquad (9)$$

where:

$$\gamma = K_o \ K_{da} \ K_b \ \frac{K_q}{D_m} \ K_t \ K_{ad}$$

$\alpha$= 90 rad/sec, $\beta$ =100 rad/sec, and $K_o$=1.6 allow for the widest bandwidth for the closed loop velocity control. This bandwidth is limited by the high frequency unmodeled dynamics in the system [12,13, and 14]. The experimental and theoretical closed loop frequency response plots (figure 7) show a bandwidth of approximately 10 rad/sec (1.7 hertz).
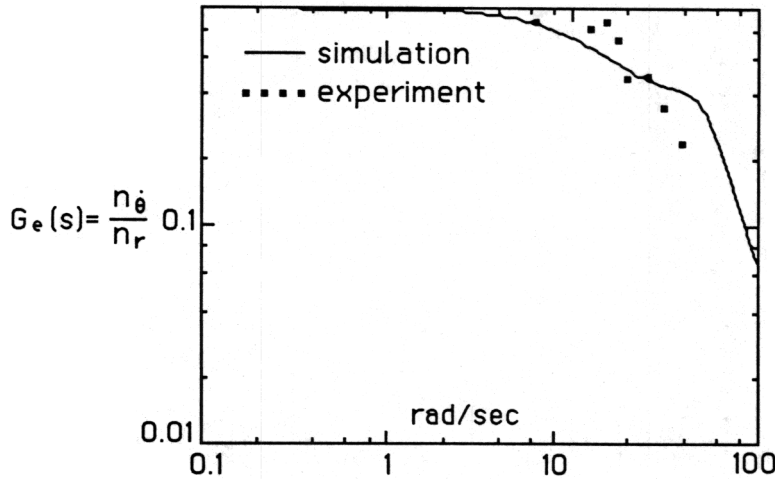


Figure 7: The Closed Loop Velocity Dynamic Behavior

The next level of control involves the design of a compensator that operates on the contact force between the extender and the human. The emphasis of the human arm model is on the functional relationship between the dynamic input and output properties of the human arm. Therefore, there is less concern about the internal structure of the components in the model. The particular dynamics of nerve conduction, muscle contraction and central nervous system processing are implicitly accounted for in constructing the dynamic model of the human arm. With regard to the above assumption two variables affect the human arm trajectory: 1) the commanded trajectory issued from the human central nervous system, $u_h$, and 2) the external force on the human arm imposed by the extender, $f_h$. The integration of the above two dynamical properties results in the dynamic equations of the human arm.

$$y_h = G_h(u_h) + S_h(f_h) \qquad (10)$$

Whenever a force is applied to the human arm, the end-point of the human arm will move in response. The sensitivity function $S_h$, is defined as a mapping from the imposed forces, $f_h$, on the hand to the resulting displacement of the human hand. In the simplest case, one can think of $S_h$ as the reciprocal of the hand muscles. $G_h$ represents the mapping from commanded trajectory issued from the human central nervous system to the human hand position, $U_h$. $G_h$ and $S_h$ are generally nonlinear mappings, however in this example they can be considered as transfer functions that map $U_h$ and $f_h$ to $y_h$. Figure 8 shows the basic structure for the closed loop control system of the one dof experimental extender. Part II describes in detail how this block diagram is constructed. E represents the physical compliance of the human arm flesh and the force sensor which is located between the human arm and the extender. Since the force sensor is very stiff, E will be dominated by the physical compliance of the flesh. Force sensor amplifier gain, $K_f$, translates the contact force to a voltage, which is then fed into the computer.
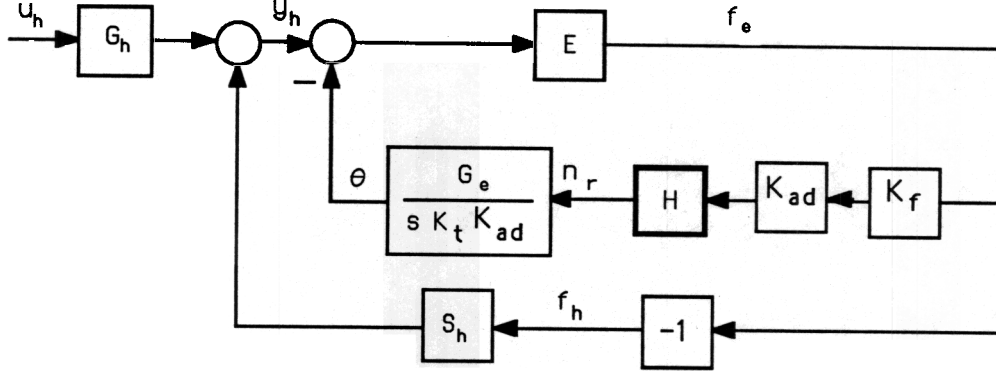


Figure 8: The difference between the robot position, $\Theta$, and the human arm position, $y_h$, results in contact force, $f_e$. The contact force $f_e$ affects the human arm in the feedback form via $S_h$. E: Flesh Compliance (120lbf/rad at DC), $S_h$: Arm Sensitivity (0.01 rad/lbf at DC), $K_f$: force amplifier gain (.095 V/lbf)

The transfer function for the position of the extender is as follows:

$$\frac{\Theta}{U_h} = \frac{G_e\,H\,K_f\,E\,G_h}{G_e\,H\,K_f\,E + s\,K_t(1+E\,S_h)}$$

From equation 11, the larger H is chosen to be, the closer $\Theta$ will be to $U_h$ and in the limit when $H\to\infty$ then $\Theta\to U_h$ (the extender will follow the human command perfectly). However one cannot choose an arbitrarily large value for H; stability of the system in Figure 8 must also be guaranteed. Raising the gain of H will increase the extender closed loop bandwidth until a point is reached where the extender can no longer be operated in a stable manner. The linear stability condition is given by inequality 12. If one guarantees the condition[15], then the system will remain stable, however if one does not satisfy inequality 12, no conclusion can be made. However, if the system is unstable, then inequality 12 must have been violated.

$$|H| < \left|\frac{s\,K_t}{G_e\,K_f}\left(\frac{1}{E} + S_h\right)\right|$$

The above stability condition does not directly depend on the internal structure of the variables; one can use various transfer functions for $G_e$, $S_h$ or E with different orders in inequality 12. The

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[15] The stability of the system is analyzed by two methods in Part II. First, the Small Gain Theorem is used to determine a sufficient condition for stability in a completely general, unstructured, nonlinear system. Then, a frequency domain sufficient condition for stability of the linear, time invariant model is determined in. The condition for stability is determined using the multivariable Nyquist Criterion, with the "size" of the operators evaluated in terms of singular values. The stability criteria in both cases is expressed in terms of size of H in comparison with the size of other operators in the loop. It is also shown that the stability condition for linear systems is a sub-class of condition derived by Small Gain Theorem.

compensator , H, was chosen as a first order filter in order to reject high frequency components of the command signal which could adversely affect system stability and performance.

$$H = \frac{K_h}{\tau s + 1} \qquad \tau = .05 \text{ sec} \tag{13}$$

It was observed experimentally that the closed loop system remains stable for all $K_h < 0.6$. Figures 9 and 10 show two stable cases where the extender velocity is proportional with the contact force. Figure 11 shows an experiment with $K_h = 1.7$ where the system becomes unstable and oscillates. Figure 12 shows that the stability criteria has been violated for $K_h = 1.7$.
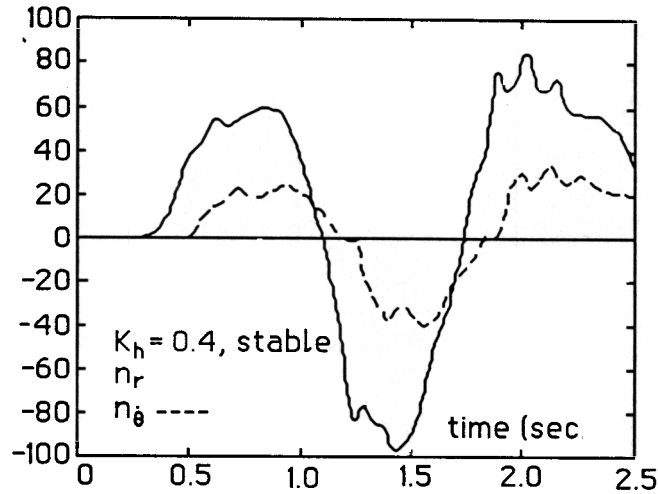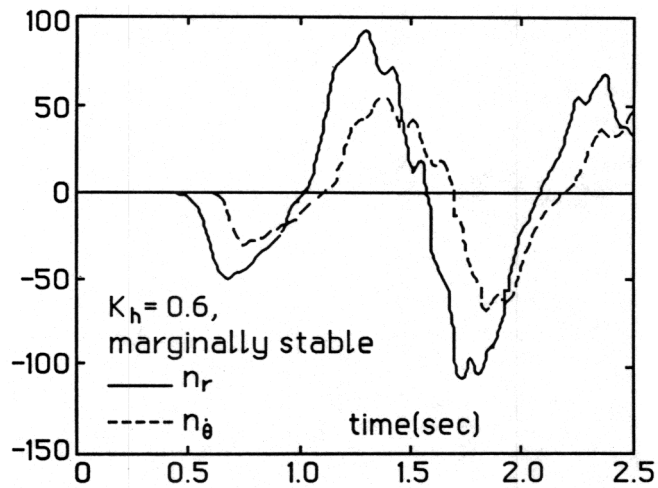


Figure 9: Stable, ($K_h=0.4$)
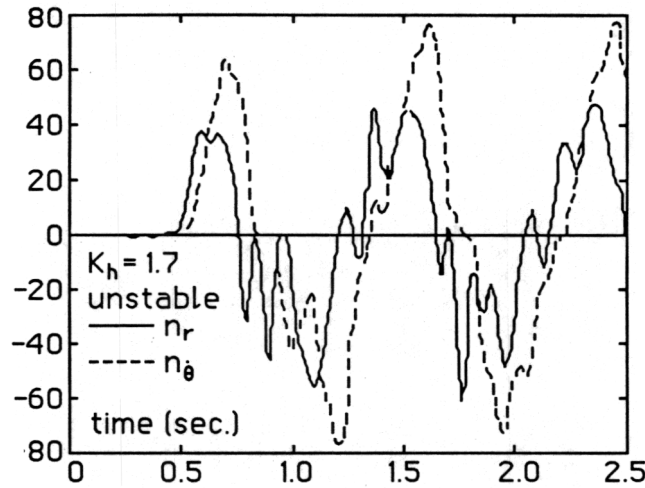


Figure 10: Marginally Stable, ($K_h = .6$)

**Figure 11:** With $K_h = 1.7$ (unstable case), the human and extender are oscillating 180° out of phase. The extender velocity increases with time.
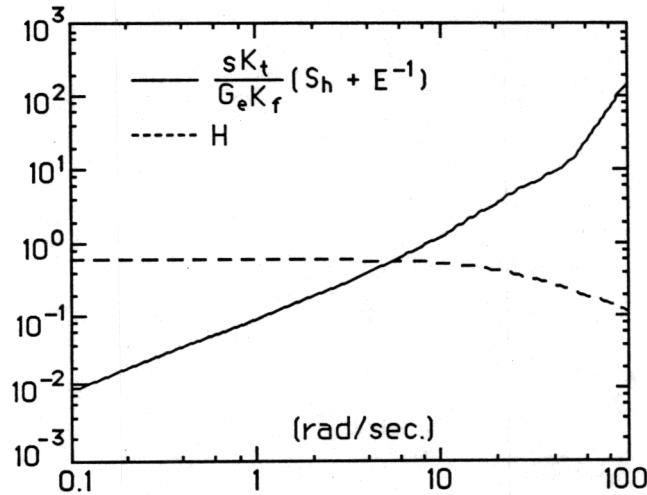


**Figure 12:** With $K_h=1.7$ the system exhibits instability; inequality 12 is not satisfied.

The exact stability can be examined by observing the root locus of the closed loop system. The root locus approaches the imaginary axis as the compensator gain $K_h$ approaches unity. Thus, the root locus analysis predicts stable operation for $K_h < 1$ while the system experimentally exhibits stable maneuver for $K_h < .6$. The stability condition expressed by inequality 12 is a sufficient condition only and it cannot predict instability. Examining inequality 12 leads to a smaller value for $K_h$ to guarantee the stability, than the one offered by root locus. Although the stability criterion expressed by inequality 12 leads to a more conservative stability condition, it does not depend on the internal structure of the extender and human arm models.

## 4. SUMMARY AND CONCLUSION

This paper has presented the concept of the extender, which is a manipulator to amplify the strength of a human. Extenders are distinguished from conventional man amplifiers due to their exchange of power and information signals when interacting with the human. The instability of such interaction between the human and extender has been addressed. A hydraulic experimental single degree of freedom extender has been built and tested to verify the control and stability criterion addressed in Part II. A multi degree of freedom extender is being built at the University of Minnesota for research work on the extender constrained maneuvers.

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