

Force Augmentation in Human-Robot Interaction

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ABSTRACT

A human's ability to perform physical tasks is limited, not by his intellect, but by his¹ physical strength. If, in an appropriate environment, a machine's mechanical power is closely integrated with a human arm's mechanical strength under the control of the human intellect, the resulting system will be superior to a loosely integrated combination of a human and a fully automated robot. Therefore, we ought to develop a fundamental solution to the problem of "extending" human mechanical power via integrating with a robot. "Extenders" are defined in this work as a class of robot manipulators worn by humans to increase human mechanical strength, while the wearer's intellect remains the central control system for manipulating the extender. The human, in physical contact with the extender, exchanges power and information signals with the extender. The analysis in this paper focuses on the dynamics and control of the robotic systems worn by humans. General models for the human, the extender, and the interaction between the human and the extender are developed. The stability of the system of human, extender, and object being manipulated² is analyzed and the conditions for stable maneuvers are derived. An expression for the extender performance is defined to quantify the force³ augmentation. The trade-off between stability and performance is described. The theoretical predictions are verified experimentally.

INTRODUCTION

Extenders are defined as a class of robot manipulators which extend the strength of the human arm while maintaining human control of the task. The defining characteristic of an extender is the transmission of both power and information signals. The extender is worn by the human; the physical contact between the extender and the human allows direct transfer of mechanical power and information signals. 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 a control system for the extender, while the extender actuators provide most of the strength necessary for the task. The human becomes a part of the extender, and "feels" a scaled-down version of the load that the extender is carrying. The extender is distinguished from a conventional master-slave system; in a conventional master-slave system, the human operator is either at a remote location or close to the slave manipulator, but 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 cannot directly exchange mechanical power. A separate set of actuators is required on the master to reflect forces felt by the slave back to the human operator.

The input command to the extender is derived from the contact forces between the extender and human, and the forces between the extender and the environment. The contact forces between the human and extender are measured, appropriately modified (in the sense of control theory to satisfy performance and stability criteria), and used as a part of the input to the extender. These forces also help maneuvering the extender because they are directly imposed on the extender. The force reflection occurs naturally in the extender system, because the contact forces between the human and extender let the human feel a scaleddown version of the actual environmental forces on the extender. For example, if an extender is employed to manipulate a 100 lbf object, the human may feel 10 lbf while the extender carries the rest of the load. The 10 lbf contact force is used not only to manipulate the object, but also to generate the appropriate signals to the extender controller.

We first describe the dynamic behavior of the extender and human, and their interaction. Then we derive the stability condition and performance specifications for the system of extender, human, and environment. The expressions for performance and closed-loop stability reveal the trade-offs between the degree of performance and the stability range. This leads to the last Section which gives a detailed theoretical and experimental description of the stability and performance of a prototype extender. The history and background relevant to this work, in particular work accomplished at General Electric Company, is described in references 2 and 3.



Figure 1: Schematic of the multi-degree-of-freedom extender being built at the University of Minnesota.

MODELING

The dynamic behavior of the extender, the human, and the environment is represented by the block diagram of Figure 2 as a set of relationships between inputs and outputs. To understand the proposed control law, we use linear control theory for a single-degree-of-freedom system (along the X direction of the XY table of Figure 3); thus, we can employ the rich concepts of linear control theory. The extension of the

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

 $^{^2}$ In this article, the word *environment* has has been used to represent any object being manipulated or pushed by the entender.

³ In this article, "force" implies force and torques, and "position" implies position and orientation.

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proposed method to multivariable and nonlinear systems has been discussed in references 2 and 3.

In the upper left part of the block diagram, the force imposed by the human arm on the extender, f_h is the result of two inputs⁴. The first input, u_h, is issued by the human central nervous system; it is assumed that the form of u_h is not known other than it is human thought deciding to impose a force on the extender. The second input, x, is the position of the extender along the X direction. Thus, we can think of the extender motion as a position disturbance occurring on the force-controlled human arm. If the extender is stationary, the force imposed on the extender is a function only of commands from the central nervous system. However, if the extender moves, the force imposed on the extender is a function not only of the central nervous system commands but also of the motion of the extender. T, the human arm "sensitivity" transfer function (or impedance), is the disturbance rejection property of the human arm: if the magnitude of T is small, the extender motion has a small effect on the force, f_h . In equation 1, the transfer function T maps the extender position, x, onto the contact force between the human and extender, f_h.

$$f_{h} = u_{h} - T \times$$
(1)

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The middle part of the block diagram represents the extender interacting with the human (worn by a human) and the environment. It is assumed that the extender primarily has either a closed-loop velocity controller or a closed-loop position controller (a positioning controller has been used in this research work). Choosing a primary stabilizing compensator⁵ for the extender has been motivated by the following two issues:

- 1) It is important for human safety that the extender remain stable when not worn by a human. A closed-loop velocity controller or a closed-loop position controller keeps the extender stationary when not worn by a human.
- 2) The design of the primary stabilizing compensator lets the designers deal with the robustness of the extender without getting involved in the dynamics of the human and the object being manipulated by the extender.
- 3) The primary stabilizing compensator eliminates the effects of frictional forces in the joints and the transmission mechanism and allows for a more definite dynamic behavior for the extender.

The selection of a primary stabilizing compensator is not discussed here; a variety of compensators can be used to stabilize the extender in the presence of uncertainties. (See reference 8 for a nonlinear tracking control method and reference 4 for robust linear servo control methods.) These compensators will also lead to decoupled and linearized closed-loop behavior for the extender. The extender closedloop position system that is created via the primary stabilizing compensator is modeled by transfer function G. Regardless of the type of primary stabilizing compensator, the extender position, x, results from two classes of inputs: first, the electronic command u to the extender closed-loop position system, and second, the forces imposed on the extender. Here, the motion of the extender is influenced by two forces: the first force, f_h , is imposed by the human on the extender, and the second force, fn, is imposed by the environment on the extender. Sh, the extender sensitivity

transfer function, maps the human force, f_h , onto the extender position, x: if the gain of S_h is small, the extender has a small response to the human force, f_h . Similarly, S_n maps the environmental force⁶, f_n , onto the extender position, x. The transfer functions, G, S_h , and S_n in equation 2 help form an expression for the extender position, x.

$$x = G u + S_h f_h + S_n f_n$$
 (2)



Figure 2: The major elements of human-machine interaction are shown in this figure where the parallel transfer of power and information signals is observed. The power transfer between the extender and the rest of system (environment and human) occurs via S_n and S_h. H_h and H_n residing in the computer, generate command signals to the extender closed-loop position system.

The extender is used to manipulate heavy objects or to impose large forces on objects. We define E as a transfer function representing the environmental dynamics and p as the equivalent of all external forces imposed on the environment. Referring to the upper right part of Figure 2, equation 3 provides a general expression for the force imposed on the extender, f_n , as a function of x.

(3)

$$f_n = -E \times + P$$

In the example of accelerating a mass m, E is a transfer function such that $E = m s^2$ and p = 0. One can think of p as the equivalent of all the forces on the extender endpoint which do not depend on \times and other system variables. One example of p can be observed when another human is holding and maneuvering the extender endpoint; the force imposed on the extender endpoint by this secondary human represents p. In this article, it is assumed that p = 0.

⁴ Subscript h and n signify the human and the environment respectively.

⁵ Hereafter, the words primary stabilizing compensator refer to a feedback controller that stabilizes (by feedback) the extender when neither worn by human nor contacting environment. The extender closed-loop position system refers to the resulting closed-loop system and is represented by transfer function G.

⁶ If a closed-loop positioning system with several integrators is chosen as the extender primary controller, then S_n and S_h have small gains resulting in small extender response to f_n and f_h . The gains of S_n and S_h for non-direct drive extenders are also small.

CONTROL

In the lower part of the block diagram of Figure 2, the computer continuously accepts information signals representing the contact forces f_h and f_n . Two controllers H_h and H_n operating on the contact forces f_h and f_n are implemented in the computer.

The performance of the controller is described in the following discussions. If U, U_h , and p in Figure 2 are zero (i.e., the input to the extender is zero, the human has no intention of maneuvering the extender, and no other forces are imposed on the extender) and H_h and H_h are chosen to be zero, the interaction force between the human and the extender is zero. Now suppose that the human arm has insufficient strength to move the extender load easily. If the human decides to move his hand (i.e., U_h becomes nonzero) and U, p, H_h , and H_n are still zero, a small extender motion develops from the interaction force between the extender and the human. The extender motion is trivial if S_h has a small gain, even though the interaction force may not be small.

If a human has insufficient strength to move the extender under a load, H_h acts as a controller to move the extender (and the human hand) to the desired location. H_b is of paramount importance, and actually decides how fast and how far the extender (and the human hand) can move. The purpose of H_h is to increase the effective strength of the human by increasing the apparent sensitivity of the extender. This is done by using the interaction force between the extender and the human as an input to the extender closed-loop position system (Figure 2). The interaction force is measured and passed through the compensator H_h to properly modify the interaction force. (At this point, there is no restriction on the structure and size of H_b.) The output of this compensator is then used as an extender input command, U. Note that the mapping G H_h acts in parallel to S_h and thus increases the apparent sensitivity of the extender. For a greater increase in this sensitivity, Figure 2 suggests choosing a larger gain for H_h. However, designers do not have complete freedom in choosing the structure and magnitude of H_h: the closed-loop system must remain stable for any chosen value of H_h.

Compensator H_n is also chosen to generate compliancy in the extender, but in response to forces imposed on the extender endpoint [1, 5, 6, 9]. H_n is a controller that shapes the extender's response to external forces. Just as external forces impede human arm motion, we want to create a behavior in which external forces impede extender motion.

CLOSED-LOOP STABILITY

A sufficient condition for stability of the closed-loop system of Figure 2 is developed by the Nyquist Theorem. This sufficient condition results in a class of compensators $(H_h \text{ and } H_n)$ which guarantee the stability of the closed-loop system in Figure 2. Note that the stability condition derived in this section does not give any indication of system performance, but only ensures a stable system. This stability condition also clarifies the trade-off between performance and closed-loop stability.

An assumption is made that the system in Figure 2 is stable when $H_h = H_n = 0$. The plan is to determine how robust the system is when the term $(G H_h T + G H_n E)$ is added to the feedback loop. Note that there are four elements in the feedback loop: $S_h T$ and $S_n E$ represent the natural feedback loops which occur as a result of the interaction between the human, extender, and environment while $G H_h T$ and $G H_n E$ represent the controlled feedback loops. If the controllers in the feedback loop are eliminated by setting $H_h = H_n = 0$, the system reduces to the case where a human wearing the extender is in contact with an environment, but the command input to the extender closed-loop position system is zero. The goal is to obtain a sufficient stability condition when H_h and H_n are added to the system. To achieve this, the Nyquist criterion [7] is used. The following assumptions are made:

1. The closed-loop system in Figure 2 is stable when $H_h=H_n=0$. It is assumed that the system remains stable when the human, environment, and extender are in contact and no feedback is used in the system.

2. H_h and H_h are chosen as stable linear transfer functions. Therefore the loop transfer function, $(S_h T + S_n E + G H_h T + G H_n E)$, has the same number of right half-plane poles as $(S_h T + S_n E)$. For convenience in stability analysis we assume $A = (S_h T + S_n E)$ and $B = (S_h T + S_n E + G H_h T + G H_n E)$.

According to the Nyquist criterion, the system shown in Figure 2 remains stable as long as the number of anticlockwise encirclements of B around the origin of the splane is equal to the number of unstable poles of the loop transfer function, B. By assumptions 1 and 2, A and B have the same number of unstable poles. Assuming that the system is stable when $H_h = H_n = 0$, the number of encirclements of the origin by (1+ A) is equal to the number of unstable poles in A. When compensators H_h and H_n are added to the system, the number of encirclements of the origin by (1+B) must be equal to the number of unstable poles in B in order to guarantee closed-loop stability. Because of the assumption that the number of unstable poles in A and B are identical, (1+ B) must have exactly the same number of encirclements of the origin as (1 + A). In order to guarantee equal encirclements by (1 + B) and (1 + A), insurance is needed so that (1+ B) does not pass through the origin of the splane for all frequencies.

 $|1 + S_h T + S_h E + GH_h T + GH_h E| \neq 0 \quad \forall \omega \in (0, \infty)$ (4)

A more conservative condition can be written as:

 $| GH_hT + GH_nE | < | 1 + S_hT + S_nE | \forall \omega \in (0, \infty) (5)$

Inequalities 4 and 5 express the stability condition of the closed-loop system in Figure 2. By inspection of inequalities 4 and 5, it can be observed that the smaller H_h and H_h are, the larger the stability range is. If a high gain positioning system is designed as the primary compensator for the extender, then S_h and S_h are rather small and stability condition 4 reduces to:

 $\begin{vmatrix} GH_h T + GH_n E + 1 \end{vmatrix} \neq 0 \qquad \forall \omega \in [0, \infty]$ (6) or $(GH_h T + GH_n E) \neq -1 \qquad \forall \omega \in [0, \infty]$ (7)

or $(GH_h T + GH_n E) \neq -1 \quad \forall \omega \in (0, \infty)$ (7) One sufficient condition to guarantee inequality 7 is:

The angle of $(GH_hT + GH_hE) < 180 \quad \forall \omega \in [0, \infty)$ (8) whenever $|GH_hT + GH_hE| = 1$

Inequality 8 states that guaranteeing stability of the closedloop system requires selecting H_h and H_n such that the phase margin for the loop gain of $(GH_hT + GH_nE)$ is positive.

PERFORMANCE

This section addresses the following question: what dynamic behavior should the extender have in performing a task? The resulting performance specification does not assure the stability of the system in Figure 2 but does let designers express what they wish to have happen during a maneuver if instability does not occur. We show that designers must accept a trade-off between performance and closed-loop stability.

The following example describes a performance specification for the extender. Suppose the extender is employed to manipulate an object through a completely arbitrary trajectory. It is reasonable to ask for an extender dynamic behavior where the human feels scaled-down values of the forces on the extender. Thus, the human has a

natural sensation of the forces required to maneuver the load: the acceleration, centrifugal, coriolis, and gravitational forces associated with an arbitrary maneuver. This example calls for masking the dynamic behavior of the extender, human, and load via the design of H_h and H_n such that a desired relationship is guaranteed between f_h and f_n . Without any proof, it is stated that only one relationship between two variables (from among three variables f_h, f_n, and x) is needed to specify a unique behavior for the extender. Note that equation 3 has already established a relationship between between f_n and x via E when p=0. If a relationship between f_n and f_h is specified, then other relationships (for example, between f_h and x) cannot be specified. This is true because substituting f_n from equation 3 into the specified relationship between f_{n} and f_{h} results in a relationship between x and f_h . Therefore, the objective is to choose H_n and H_h so that one relationship can be established between f_h and f_n or between f_h and x. The following equations are suggested as the two target relationships:

$$f_h = Q f_n \tag{9}$$

$$f_h = R \times$$
(10)

Q and R are arbitrary nonlinear target dynamics. The first equation, which is the most natural design specification for extenders, allows the designers to specify a relationship between the forces f_h and f_n . The second relationship establishes an impedance for the extender. The following describes a design example where equation 9 is of interest.

Suppose the purpose is to guarantee the relationship between the forces f_h and f_n (i.e. equation 9). A primary stabilizing compensator can be designed so that the transfer functions S_n and S_h have small gains and G creates an approximately unity gain from \cup to x. This can be achieved by using a position controller that creates a large open-loop gain in the extender itself. For example, if several integrators are used in the extender primary stabilizing compensator, then S_h and S_n are small, which results in small extender response to f_h and f_n . The governing dynamic equation when the extender closed-loop position system is insensitive to f_h and f_n is:

$$x \approx G H_h f_h + G H_n f_n \tag{11}$$

Employing equations 3 and 11 (when p=0) results in the following equation for the ratio between f_h and f_n .

$$\frac{f_h}{f_n} = -\frac{GH_nE+1}{GH_hE}$$
(12)

We must choose H_h and H_n such that the ratio of the forces defined in equation 12 equals $-\alpha$ where α is a constant smaller than unity and it represents the force amplification (the negative sign of $-\alpha$ represents the opposite directions of f_h and f_n). One solution can be obtained by choosing H_n arbitrarily and calculating H_h from equation 13.

$$H_{h} = \left[\frac{1}{GE} + H_{h} \right] \frac{1}{\alpha}$$
(13)

Designers, however, do not have complete freedom in choosing the structure and magnitude of H_n : the closed-loop system must remain stable for any chosen value of H_n .

EXPERIMENTAL ANALYSIS

A computer-driven XY table has been employed as the extender simulator (Figure 3). A person holding a handle on the table maneuvers heavy loads. Due to the low pitch angle of the lead-screw mechanism, the XY table is not back-drivable. A piezoelectric force sensor between the handle and the table measures the human's force, f_h , in two

orthogonal directions. Another piezoelectric force sensor between the table and the load measures the force imposed on the extender by the environment, f_n . In addition to the piezoelectric force sensors, other sensing devices include a tachometer and an encoder (with a corresponding counter) to measure the speed and position of the table. A microcomputer is used for data acquisition and control. For brivity, only the analysis along the x-direction has been discussed.



Figure 3: The experimental extender employed for verification of the control law.

The primary stabilizing compensator for the table is designed to yield the widest bandwidth for the closed-loop position transfer functions, G, while guaranteeing the stability of the closed-loop positioning system in the presence of bounded unmodeled dynamics in the table. The analytical value for G which represents the closed-loop positioning system for the table along the X direction is given by equation 14⁷.

$$G = \frac{x}{u} = \frac{1}{\left[\frac{s^2}{31^2} + \frac{s}{25} + 1\right] \left[\frac{s^2}{265^2} + \frac{s}{294} + 1\right]} \quad \text{cm/cm (14)}$$

The above transfer function is verifed experimentally via a frequency response method and its theoretical and experimental values are plotted in Figure 4.



rad/sec in the x-direction.

The table is employed to move a mass (as shown in Figure 3). Substituting for m in equation 3 ($E=ms^2$ when p=0) results in equation 15 for the environment dynamics along the X direction.

$$E = 5 s^2 N/cm$$
 (15)

Figure 5 depicts the experimental and theoretical values of the environment dynamics.

⁷ The development of the position controllers for the table has been omitted for brivity.



Figure 5: The Experimental and Theoretical Plot of E

The model derived for the human arm does not represent the human arm sensitivity T for all configurations of the arm; it is only an approximate and experimentally verified model of the author's arm in the neighborhood of the Figure 3 configuration. If the human arm behaves linearly in the neighborhood of the horizontal position, T is the human arm impedance. For the experiment, the author gripped the handle, and the extender was commanded to oscillate along the X-direction via sinusoidal functions. At each oscillation frequency, the operator tried to move his hand to follow the extender so that zero contact force was maintained between his hand and the extender; i.e. $u_h=0$. Since the human arm cannot keep up with the high-frequency motion of the extender when trying to maintain zero contact forces, large contact forces and consequently, a large T are expected at high frequencies. Since this force is equal to the product of the extender acceleration and human arm inertia (Newton's Second Law), at least a second-order transfer function is expected for \top at high frequencies. On the other hand, at low frequencies (in particular at DC), since the operator can follow the extender motion comfortably, he can always establish almost constant contact forces betwen his hand and the extender. This leads to the assumption of a constant transfer function for T at low frequencies where contact forces are small for all values of extender position. Based on several experiments, at various frequencies, the best estimate for the author's hand sensitivity is presented by equation 16.

$$T = 0.1 \left(\frac{s^2}{2.5^2} + \frac{s}{2.19} + 1 \right) \qquad N/cm \qquad (16)$$

Figure 6 shows the experimental values and fitted transfer function for the human arm dynamic behavior.

The design objective is to decrease the force transferred to the human arm so the human feels the scaleddown values of the force imposed by the load on the table. This requires that $f_h = -\alpha f_n$ where α is a scalar smaller than unity and represents the reduction of the force transmitted to the human arm. H_n is chosen as:

$$H_n = \frac{0.1}{s^2}$$
 cm/N (17)

Substituting G, E, T, and H_n from equations 14, 15, 16, and 17 into equation 13 gives H_n .

$$H_{h} = \frac{\frac{s^{2}}{37.97^{2}} + \frac{s}{37.50} + 1}{3.33 \,\alpha \, s^{2}} \qquad cm/N \qquad (18)$$



Figure 7 verifies that the system is stable when H_n and H_h in equations 17 and 18 are employed to drive the system; since $|GH_hT + GH_nE + 1|$ (inequality 6) is always nonzero for various values of α , the system stability is guaranteed. The above values of H_h and H_n result in $f_h = \alpha$ f_n; Figure 8 shows the theoretical force ratio $|f_h/f_n|$ for various values of α where the force amplification is constant within 20 rad/sec. This implies that the force imposed by the human will be equal to a scaled-down value of the extender force as long as the frequency range of the motion in the system is within 20 rad/sec. Figure 9 depicts the experimental and theroretical value of $|f_h/f_n|$ when α is chosen to be 0.2. The experimental value of $|f_h/f_n|$ has been achieved by calculation of the FFT of f_n and f_h . This experiment also confirms the proportionality of the forces within the range of 20 rad/sec.



Figure 10 depicts the table motion in the experiment where the human maneuvers the table irregularly (randomly). Figures 11 and 12 both show f_n and f_h measured during the experiment. Figure 11 presents the experimental values of f_n .

versus f_h . Both figures confirm that the environmental force is five times larger than the human force.

SUMMARY AND CONCLUSION

This paper discusses constrained motion in a class of human-controlled robotic manipulators called extenders. Extenders amplify the strength of the human operator, while utilizing the intelligence of the operator to generate spontaneously the command signal to the system. System performance is defined as amplification of human force. It is shown that the greater the required amplification, the smaller the stability range of the system is. A condition for stability of the closed-loop system (extender, human and environment) is derived, and, through experimentation, the sufficiency of this condition is demonstrated.



Figure 8: The theoretical plot of f_h/f_n for various values of α .



Figure 9: The Theoretical and Experimental plot of $|f_h/f_n|$ for $\alpha = 0.2$.



Figure 10: The Table Motion



Figure 11: f_n and $-f_h$ when the human maneuvers the table randomly. f_h is five times smaller than f_n .



Figure 12: $f_n vs f_h$ when a force amplification of 5 has been chosen to design $H_n vs H_h$.

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