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Stability and Performance of Robotic Systems Worn by Humans

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ABSTRACT

A human's ability to perform physical tasks is limited, not by his intellect, but by his[2] 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 manipulated[3] is analyzed and the conditions for stable maneuvers are derived. An expression for the extender performance is defined to quantify the force[4] 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 scaled-down 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.

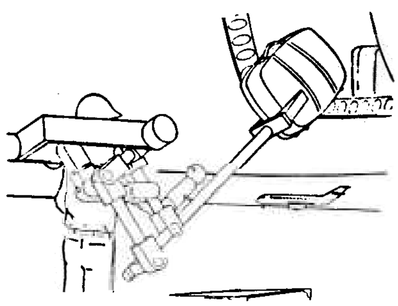

Figure 1: Schematic of the multi-degree-of-freedom extender being built at the University of Minnesota.

MODELING

The dynamic behavior of the extender, the human, and the environment is represented by the block diagram of Figure 2

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[1] This research is supported by NSF (EET 8809088).

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

[3] In this article, the word *environment* has been used to represent any object being manipulated or pushed by the entender.

[4] In this article, "force" implies force and torques, and "position" implies position and orientation.

as a set of relationships between inputs and outputs. To understand the proposed control law, we use rich concepts of linear control theory; the extension of the proposed method to multivariable and nonlinear systems has been discussed in references 2 and 3. All functions of Figure 2 are $n\times1$ vectors while all tranfer functon matrices are $n\times n$ square matrices.

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 inputs[5]. 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.

$$f_h = u_h - T\,x \qquad (1)$$

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 compensator[6] 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 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 9 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 closed-loop 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, f_n, is imposed by the environment on the extender. S_h, 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 force[7], 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.

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

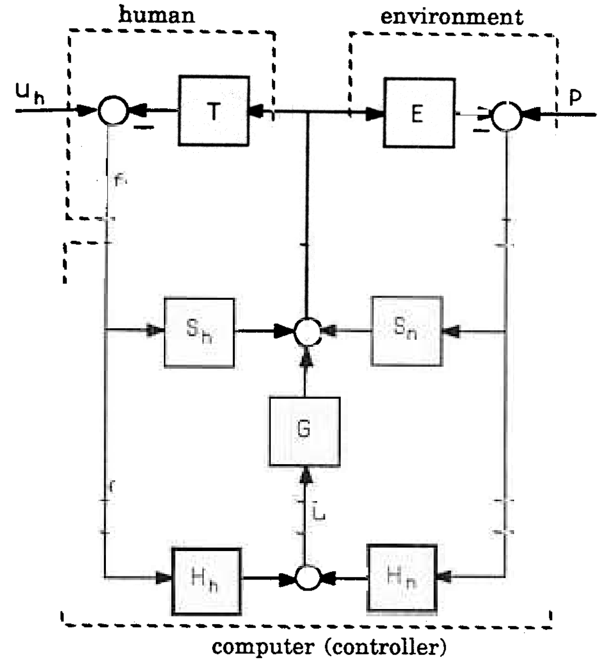

Figure 2: The major elements of human-machine interaction are shown in this figure where the parallel transfer of power and information signals is observed. The power transfer between the extender and the rest of system (environment and human) occurs via S_n and S_h. H_h and H_n residing in the computer,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

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.

$$f_n = -E\,x + p \qquad (3)$$

In the example of accelerating a mass m, E is a transfer function such that $E = m s^2$ and $p = 0$.

In another example (Figure 3) a single-degree-of-freedom extender swinging clockwise, compressing an environmental

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[5] Subscript $_h$ and $_n$ signify the human and the environment respectively.

[6] 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 matrix G.

[7] 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.

apparatus. Defining the direction of f_n as being to the extender from the environment, the torque that constrains the extender motion is a counterclockwise torque of $(K+Cs)l_{en}^2 x$ where K, C, x, and s are stiffness, damping, extender angular orientation, and the Laplace operator. This leads to $E = (K+Cs)l_{en}^2$. One can think of p as the equivalent of all the forces on the extender endpoint which do not depend on x 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 $p = 0$.

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_n 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_h 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_h.) 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, 10]. 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.

PERFORMANCE AND 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:

$$f_h = Q\, f_n \tag{4}$$

$$f_h = R\, x \tag{5}$$

Q and R are target transfer function matrices. 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 an example in which equation 4 is of interest.

Suppose the purpose is to guarantee a relationship between the forces f_h and f_n (equation 4) without concern for the relationship between f_h and x (equation 5). A trajectory controller can be designed so that S_n and S_h have small gains. This can be achieved by implementing 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 controller, 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 primary controller is insensitive to f_h and f_n is:

$$x \approx G\, H_h\, f_h + G\, H_n\, f_n \tag{6}$$

H_h and H_n are chosen as:

$$H_h = -2\; G^{-1} E^{-1} Q^{-1} \tag{7}$$

$$H_n = G^{-1} E^{-1} \tag{8}$$

Substituting H_h and H_n (equations 7 and 8) into equation 6 results in equation 9.

$$x \approx -2\, E^{-1} Q^{-1} f_h + E^{-1} f_n \tag{9}$$

Since $x = -E^{-1} f_n$, then:

$$-E^{-1} f_n \approx -2\, E^{-1} Q^{-1} f_h + E^{-1} f_n \tag{10}$$

and, consequently:

$$f_h \approx Q\, f_n \tag{11}$$

In an example illustrating the above case, an extender is used to hold a jackhammer. The objective is to decrease and filter the force transferred to the human arm so the human feels only the low-frequency force components. This requires that $f_h = -\alpha M f_n$ where, preferably, M is a diagonal transfer function matrix with low-pass filter transfer functions as members. α is a scalar smaller than unity and represents the force reduction. Choosing $Q = -\alpha M$, the required forms of H_h and H_n are as follows:

$$H_h = 2\, G^{-1} E^{-1} \frac{1}{\alpha} M^{-1} \tag{12}$$

$$H_n = G^{-1} E^{-1} \tag{13}$$

Substituting H_h and H_n from equations 12 and 13 into equation 6 results in $f_h \approx -\alpha M f_n$. The above method calls for the class of Q functions that are exactly invertible or at least can be inverted approximately. For example, if M is chosen as a first-order filter, then M^{-1} in equation 12 can approximately be realized for a bounded frequency range.

Using Multivariable Nyquist Theorem [7], inequality 14 can be used as a condition for stability [2,3].

$$\sigma_{max}(GH_hT + GH_nE) < \sigma_{min}(I + S_hT + S_nE) \quad \forall\omega \in (0,\infty) \qquad (14)$$

If a high gain positioning system is designed as the primary compensator for the extender, then S_n and S_h are rather small and the stability condition reduces to:

$$\sigma_{max}(GH_hT + GH_nE) < 1 \qquad \forall\omega \in (0,\infty) \qquad (15)$$

For a single-degree-of-freedom extender, the stability condition of 14 reduces to:

$$|GH_hT + GH_nE| < |1 + S_hT + S_nE| \qquad \forall\omega \in (0,\infty) \qquad (16)$$

The larger H_h is chosen to be, the smaller the ratio of f_h to f_n is. Loosely speaking, large H_h allows the human to manipulate large objects or to impose large forces onto the environment. On the other hand, the stability conditions given above require small values for H_h to guarantee the stability of the system. This trade-off between stability and performance is illustrated experimentally in the next section.

EXPERIMENTAL ANALYSIS

A single-degree-of-freedom extender (Figure 3) is used to verify experimentally the theoretical predictions for extender stability and performance. This experimental extender consists of an outer tube (39.5 lbf) and an inner tube. The human arm, wrapped in a cylinder of rubber for a snug fit, is located in the inner tube. A piezoelectric load cell, placed between these tubes, measures the interaction force between the human arm and the extender, f_h. Another piezoelectric force cell, set between the extender and the environment, measures the interaction force between the extender and environment, f_n. A rotary hydraulic actuator, mounted on a solid platform, powers the outer tube of the extender. The actuator shaft, supported by two bearings, is connected to the outer tube to transfer power. In addition to the piezoelectric load cells, other sensing devices include a tachometer and an encoder (with a corresponding counter) to measure the angular speed and position of the motor shaft. An automobile strut, mounted on a custom fixture below the extender, is the experimental environment. An IBM/AT computer is used for data acquisition and control. Based on the information from these sensors, a control algorithm calculates a command signal which is sent to the extender servo controller board via a digital-to-analog (D/A) converter.

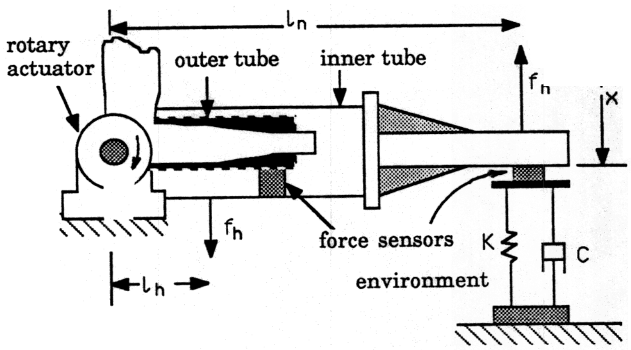

Figure 3: Experimental Extender

Figure 4 shows the *extender closed-loop position system*, G, from u to the extender position x which is stabilized by position and velocity feedback gains. G_p and G_d are the transfer functions of the open-loop extender that show how the extender responds to the input current, I, and the forces, f_n and f_h. The moment arm l_h, representing the effect of the human force, is about one-third of l_n. The servo controller board, with a gain of K_b [8], outputs a current proportional to the command voltage, resulting in a displacement of the servovalve spool. The extender velocity is measured for feedback by a tachometer with a gain of K_t and is fed to the computer by an analog-to-digital convertor with a gain of K_{ad}. The extender position is measured by an encoder via a parallel IO board with a gain of K_{IO}. The pre-compensator K_o is used as a constant gain to change the input units. K_1 and K_2 are position and velocity gains and K_{da} is the digital-to-analog convertor gain.

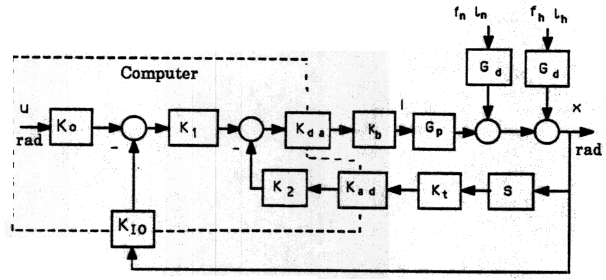

Figure 4: Block Diagram of the Closed-loop Position Controller, Tach. gain: K_t=0.169 volts/(rad/sec), Servo controller board gain: K_b= 0.00465 ampere/volt, Digital to Analog Convertor: K_{da}=10 volts/2048, Analog to Digital Convertor: K_{ad}=2048/1.25 volts, Parallel IO gain: K_{IO}=1592 number/rad, Pre-compensator : K_o=1592 number/rad, Position gain: K_1 =.94, Velocity gain: K_2 = .00977

Equations 17 and 18 are the experimentally verified transfer functions for G_p and G_d.

$$G_p = \frac{x}{I} = \frac{355}{s\left(\frac{s^2}{1560.25} + \frac{s}{43.89} + 1\right)} \quad \text{rad/Ampere} \qquad (17)$$

$$G_d = 135 \times 10^{-7} \frac{\frac{s}{23.6} + 1}{s\left(\frac{s^2}{1560.25} + \frac{s}{43.89} + 1\right)} \quad \text{rad/(lbf·inch)} \qquad (18)$$

Using K_1 = .94 and K_2 = 0.00977 yields the widest bandwidth for *extender closed-loop position system*, G, and guarantees the stability of the system in the presence of bounded unmodeled dynamics in the extender [4]. From Figure 4, an expression for G is derived in equation 19. Figure 5 depicts the theoretical and experimental values for the Bode plot of G.

$$G = \frac{x}{u} = \frac{1}{\frac{s^3}{18860} + \frac{s^2}{530.52} + \frac{s}{11.83}} \quad \text{rad/rad} \qquad (19)$$

S_n is defined as the sensitivity of the extender position x to f_n applied at a moment arm of $l_n = 3'$. S_h is defined as the sensitivity of the extender position to f_h applied at a moment arm of l_h=1'. By inspecting the block diagram of Figure 4 and substituting the parameter values, S_n can be found as follows:

$$S_n = \frac{x}{f_n} = 4 \times 10^{-5} \frac{\frac{s}{23.6} + 1}{\frac{s^3}{18860} + \frac{s^2}{530.52} \cdot \frac{s}{11.83}} \quad \text{rad/lbf} \qquad (20)$$

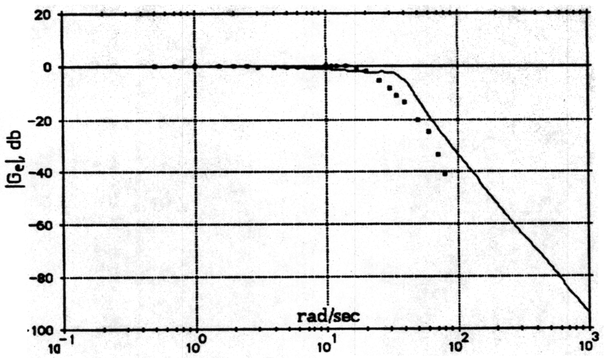

Figure 5: The Experimental and Theoretical Bode Plot of G. The extender closed loop position system has the bandwidth of about 10 rad/sec.

Since the human arm force affects the extender about three times less than the environment force, S_h is about three times less than S_n.

$$S_h = 1.34\times10^{-5}\ \frac{\frac{s}{23.6}+1}{\frac{s^3}{18860}+\frac{s^2}{530.52}+\frac{s}{11.83}+1}\ \text{rad/lbf} \quad (21)$$

An automobile strut, mounted on a custom fixture below the extender, is the experimental environment (Figure 3). This environment can be modeled as a linear spring and damper system, where inertial effects of the strut are negligible compared to the spring and damping effects. The environmental stiffness and damping are measured to be 2050 lbf/rad and 200 lbf/(rad/sec) where radians represents the angular displacement of the motor shaft.

$$E = 200s + 2050 \quad \text{lbf/rad} \quad (22)$$

The model derived for human arm here does not represent human arm sensitivity, T, for all configurations; it is only an approximate and experimentally verified model of the author's elbow in the neighborhood of the Figure 3 configuration. The extender motion x, in the case of this prototype, is a rotating motion about the elbow joint. If the human elbow behaves linearly in the neighborhood of the horizontal position, T is the human arm impedance. For the experiment, the author's elbow was placed in the extender, and the extender was commanded to oscillate via sinusoidal functions. In each frequency of the extender oscillation, the operator tried to move his hand and follow the extender so that zero contact force was created between his hand and the extender. Since the human arm cannot keep up with the high frequency motion of the extender when trying to create 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 T at high frequencies. On the other hand, at low frequencies (in particular at DC), since the operator can comfortably follow the extender motion, he can always establish almost zero contact forces between his hand and the extender. This leads to the assumption of a free derivative 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 23.

$$T = .143\, s^2 + s \quad \text{lbf/rad} \quad (23)$$

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

The design objective is to decrease the force transferred to the human arm so the human feels the scaled-down values of the force imposed by the environment. 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. Using equations 12 and 13, H_h and H_n can be written as:

$$H_h = \frac{2}{\alpha E G} \quad (24)$$

$$H_n = \frac{1}{E G} \quad (25)$$

Substituting G and E from equations 19 and 22 into equations 24 and 25 gives H_h and H_n.

$$\frac{s^3}{\ }\ .\ \frac{s^2}{\ }\ .\ \frac{s}{\ } \quad (26)$$

$$(27)$$

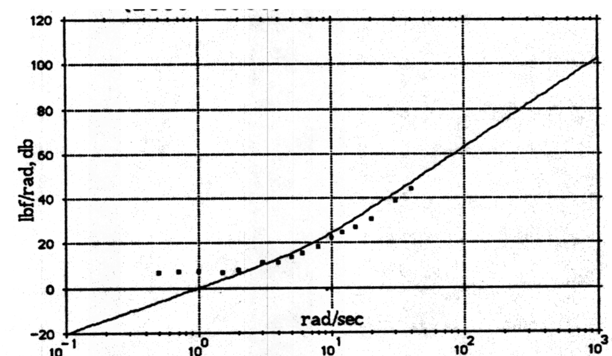

Figure 6: The Experimental and Theoretical Plot of T

Equations 26 and 27 are improper transfer functions. For implementation on the computer, two high frequency poles are added to each of the transfer functions of equations 26 and 27[8]. The above values of H_h and H_n result in $f_h = -\alpha f_n$. The designer cannot arbitrarily choose α; in order to guarantee system stability, α must be chosen to guarantee inequality 16. However, if α is small (large force amplification), inequality 16 is violated at some frequencies, and no conclusion about stability can be made. Figure 7 depicting both sides of inequality 16 shows that for guaranteed stability of the closed-loop system, α must be larger than 0.143 (seven times force amplification).

In the first set of experiments, α is chosen to be 0.5 to satisfy inequality 16, and it is shown that the closed-loop system is stable. The basic procedure for the experiment consisted of using the prototype extender to push on the fabricated environment in a series of periodic functions. The forces f_h and f_n were measured and recorded in data files. The recorded f_h was used as an input to a computer simulation encompassing the dynamic behavior of the extender, human, and environment. Figure 8 shows the simulated and experimental values of f_n along with the recorded value of f_h for a maneuver when α is chosen to be 0.5 (twice force amplification). The experimental data and theoretical predictions are in close agreement. This demonstrates the linearity between the input f_h and the output f_n. Note that the output force f_n is consistently twice the input force f_h. The second set of experiments was conducted with $\alpha = 0.03$, where the system exhibits instability in the form of oscillations (Figure 9). Inspection of Figure 7 shows that the choice of $\alpha = 0.03$ violates inequality 16. The trade-off

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8 H_1 and H_2 are divided by the force sensor and the A/D convertor gains.

between performance and stability can be observed here: the better the required performance (larger force amplification in this experiment), the narrower the stability range is. Since inequality 16 is only a sufficient condition for stability, violation of this condition does not lead to any conclusion. Figure 10 shows the experimental and simulated contact forces when α=0.1 (force amplified by a factor of 10) . The system is stable and f_n is consistently ten times larger than the force f_h, but the stability condition is not satisfied.

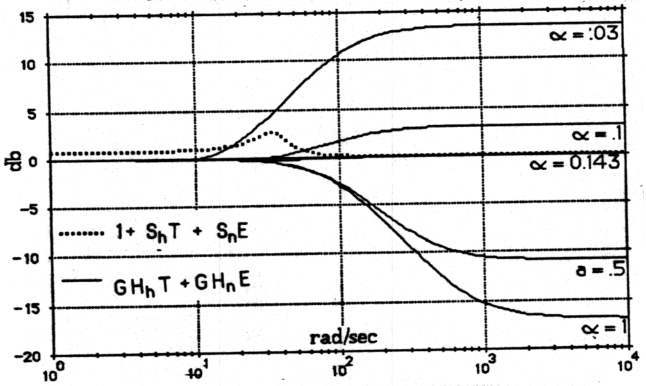

Figure 7: Inequality 16 (stability condition) is satisfied for α>0.143.

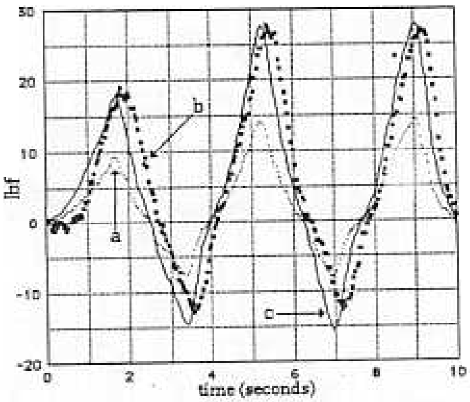

Figure 8: Stable maneuver with α=0.5 (twice force amplification) a:f_h, b: experimental f_n, c:simulated f_r

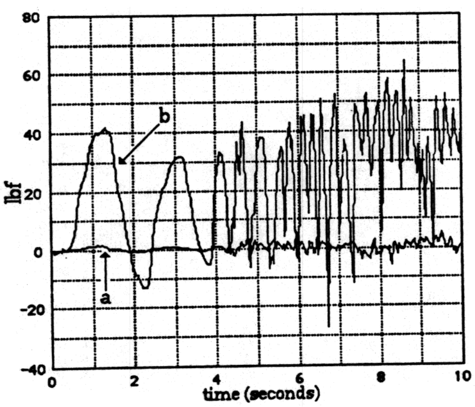

Figure 9: Unstable maneuver with α = 0.03 (thirty times force amplification). H_h and H_n violate inequality 16, a: f_h, b: experimental f_n.

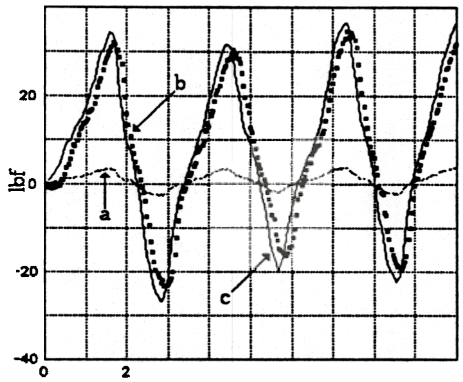

Figure 10: With α=0.1 (ten times force amplification), H_h and H_n violate the stability condition; however, the system is stable. a:f_h, b:experimental f_n, c:simulatedf_n

SUMMARY AND CONCLUSION

This paper discusses the 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 spontaneously generate the command signal to the system. A single-degree-of-freedom extender has been built for theoretical and experimental verification of the extender dynamics and control. 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 both simulation and experimentation, the sufficiency of this condition is demonstrated.

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