Stability and Performance of Robotic Systems Worn by Humans

H. Kazerooni

Mechanical Engineering Department
University of Minnesota
Minneapolis, MN 55455

ABSTRACT

A human's ability to perform physical tasks is limited, not by his intellect, but by his 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 is analyzed and the conditions for stable maneuvers are derived. An expression for the extender performance is defined to quantify the force 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 the environment, and the forces between the extender and the human. 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.
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 \( n \times 1 \) vectors while all transfer function 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, \( f_h \).

\[
f_h = u_h - T x \tag{1}
\]

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 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, \( f_n \), 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, \( x \).

\[
x = G u + S_h f_h + S_n f_n \tag{2}
\]

In the example of accelerating a mass \( m \), \( E \) is 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 \( x \).

\[
f_n = -E x + p \tag{3}
\]

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

\(^{5}\) 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 \( S_h \) and \( S_n \) have small gains resulting in small extender response to \( f_h \) and \( f_n \). The gains of \( S_h \) and \( S_n \) 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 $(K + C_s)Len^2$ where $K$, $C$, $\times$, and $s$ are stiffness, damping, extender angular orientation, and the Laplace operator. This leads to $E = (K + C_s)Len^2$. 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 $H_h$ is also chosen to generate compliancy in the extender, but in response to forces imposed on the extender endpoint $[1, 5, 6, 10]$. $H_h$ 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 $f_h$ and $x$ via $E$ when $p = 0$. If a relationship between $f_h$ and $f_n$ is specified, then other relationships (for example, between $f_h$ and $x$) cannot be specified. This is true because substituting $f_h$ from equation 3 into the specified relationship between $f_h$ and $f_n$ results in a relationship between $x$ and $f_n$. Therefore, the objective is to choose $H_h$ and $H_n$ 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:

$$f_h = Q f_n$$  \hspace{1cm} (4)

$$f_h = R x$$  \hspace{1cm} (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 $S_h$ 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 $S_h$ 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:

$$x = G H_h f_h + G H_h f_n$$  \hspace{1cm} (6)

$H_h$ and $H_n$ are chosen as:

$$H_h = -2 G^{-1} E^{-1} Q^{-1}$$  \hspace{1cm} (7)

$$H_n = G^{-1} E^{-1}$$  \hspace{1cm} (8)

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

$$x = -2 E^{-1} Q^{-1} f_h + E^{-1} f_n$$  \hspace{1cm} (9)

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

$$-E^{-1} f_n = -2 E^{-1} Q^{-1} f_h + E^{-1} f_n$$  \hspace{1cm} (10)

and, consequently:

$$f_n = Q f_h$$  \hspace{1cm} (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 $f_n = -\alpha f_h$, where, preferably, $M$ is a diagonal transfer function matrix with low-pass filter transfer functions as members. $\alpha$ 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:

$$H_h = 2 G^{-1} E^{-1} M^{-1}$$  \hspace{1cm} (12)

$$H_n = G^{-1} E^{-1}$$  \hspace{1cm} (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].

$$\sigma_{\max}(GH_h + GH_n) < \sigma_{\min}(I + S_n T + S_n E) \forall \omega \in [0, \infty)$$

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:

$$\sigma_{\max}(GH_h + GH_n) < 1 \forall \omega \in [0, \infty)$$

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

$$|GH_h + GH_n| < |1 + S_n T + S_n E| \forall \omega \in [0, \infty)$$

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 to-analog (D/A) converter.

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 converter.

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, $i$, the forces, $f_n$ and $f_h$. The moment arm $l_n$, representing the effect of the human force, is about one-third of $l_w$. The servo controller board, with a gain of $K_1$ [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 $K_{da}$. The extender position is measured by an encoder via a parallel IO board with a gain of $K_t$. The pre-compensator $K_0$ 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.

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

$$G_p = \frac{X_i}{I} = \frac{355}{s^2 + 1560.25 + 43.89} \text{ rad/Ampere}$$

$$G_d = \frac{3}{1560.25 + 43.89 + 1} \text{ rad/(lbf-inch)}$$

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 $G$.

$$G = \frac{X}{U} = \frac{18860 + 530.52 + 11.83}{s^3 + \frac{g}{s^2 + 1}} \text{ rad/rad}$$

$S_n$ 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 $l_h = 3'$. By inspecting the block diagram of Figure 4 and substituting the parameter values, $S_n$ can be found as follows:

$$S_n = \frac{1}{f_n} = 4 \times 10^{-6} \frac{8}{s^3 + 23.6 + 1} \text{ rad/lbf}$$
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 $\alpha$ 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:

$$H_h = \frac{2}{\alpha E G}$$
$$H_n = \frac{1}{E G}$$

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

$$\frac{S^3}{G^2 + S}$$

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. The above values of $H_h$ and $H_n$ result in $f_h = f_n$. The designer cannot arbitrarily choose $\alpha$; in order to guarantee system stability, $\alpha$ must be chosen to guarantee inequality 16. However, if $\alpha$ 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, $\alpha$ must be larger than 0.143 (seven times force amplification).

In the first set of experiments, $\alpha$ 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 $\alpha$ 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 $H_1$ 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 \( \alpha = 0.1 \) (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.

### 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.

### REFERENCES