THE HUMAN POWER AMPLIFIER TECHNOLOGY APPLIED TO MATERIAL HANDLING

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ABSTRACT

We define "extenders" as a class of robot manipulators worn by humans to augment human mechanical strength, while the wearer's intellect remains the central control system for manipulating the extender. Our research objective is to determine the ground rules for the design and control of robotic systems worn by humans through the design, construction, and control of several prototype experimental direct-drive/non-direct-drive multi-degree-of-freedom hydraulic/electric extenders. The design of extenders is different from the design of conventional robots because the extender interfaces with the human on a physical level. Two sets of force sensors measure the forces imposed on the extender by the human and by the environment (i.e., the load). The extender's compliances in response to such contact forces were designed by selecting appropriate force controllers. This paper gives a summary of some of the selected research efforts related to Extender Technology, during the last decade at the Human Engineering Laboratory (HEL).

1. INTRODUCTION

This article presents an overview of human-power amplification technology being developed at the Human Engineering Laboratory (HEL), University of California, Berkeley. Extenders are robotic systems worn by humans to increase human mechanical ability, while the human's intellect serves as the central intelligent control system for manipulating the load. The human becomes a part of the extender, and "feels" a force that is related to the load carried by the extender. Figure 1 shows an example of a hydraulic extender (Kazerooni and Guo 93). Some major applications for extenders include loading and unloading of missiles on aircraft; maneuvering of cargo in shipyards, foundries, and mines; or any application which requires precise and complex movement of heavy objects. The goal of our research is to determine the ground rules for a control system which lets us arbitrarily specify a relationship between the human force and the load force. In a simple case, the force the human feels is equal to a scaled-down version of the load force: for example, for every 100 pounds of load, the human feels 5 pounds while the extender supports 95 pounds. In another example, if the object being manipulated is a pneumatic jackhammer, we may want to both filter and decrease the jackhammer forces: then, the human feels only the low-frequency, scaled-down components of the forces that the extender experiences. In the most general case, one may wish an arbitrary relationship between the human force and load force as a control specification.

Three elements contribute to the dynamics and control of this system: the human operator, an extender to lift the load, and the load being maneuvered. The extender is in physical contact with both the human and the load, but the load and the human have no physical contact with each other. Forces between the human and the extender and forces between the load and the extender are measured and processed to maneuver the extender properly. These measured signals create two paths of information transfer to the extender: one from the human and one from the load. No other external information signals from other sources (such as joysticks, pushbuttons or keyboards) are used to drive the extender. The information signals sent to the extender computer must be compatible with the power transfer to the extender hardware. This is fully described in (Kazerooni 90b, Kazerooni and Guo 93).

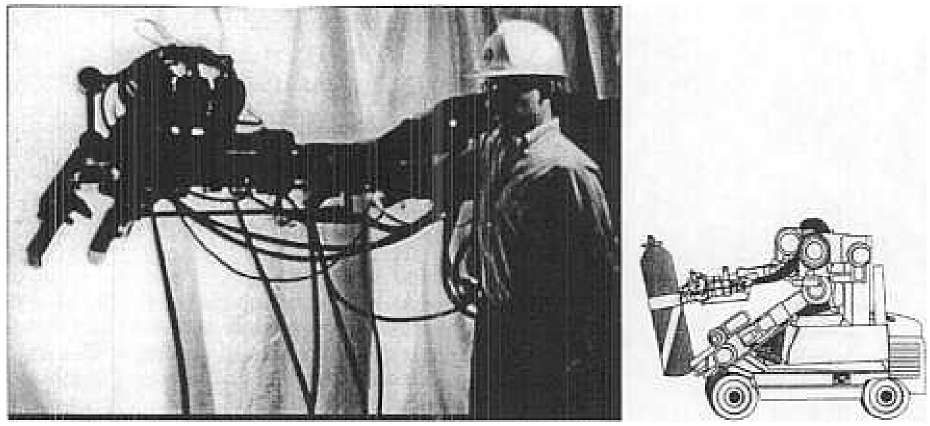


Figure 1: Experimental Six-Degree-of-Freedom Hydraulic Extender designed at UC, Berkeley.

2. WORK AT UC BERKELEY

It is important to note that previous systems (Mosher 60, Makinson 71, Clark 62, Groshaw 69) operated based on the master-slave concept (Kazerooni and Tsay 93), rather than on the direct physical contact between human and manipulator inherent in the extender concept. Unlike the Hardiman and other man-amplifiers, the extenders designed at HEL are not master-slave systems (i.e. they do not consist of two overlapping exoskeletons.) There is no joystick or other device for information transfer. Instead, the human operator's commands to the extender are taken directly from the interaction force between the human and the extender. This interaction force also helps the extender manipulate objects physically. In other words, information signals and power transfer simultaneously between the human and the extender. The load forces naturally oppose the extender motion. The controller developed for the extender translates this interaction force signal into a motion command for the extender. This allows the human to initiate tracking commands to the extender in a very direct way. The concept of transfer of power and information signals is also valid for the load and extender. The load forces are measured directly from the interface between the load and the extender and processed by the controller to develop electronic compliancy in response to load forces (Kazerooni, Waibel 91, Kazerooni 90a). In other words, information signals and power transfer simultaneously between the load and the extender. Several prototype experimental extenders were designed and built to help clarify the design issues and verify the control theories for various payloads and maneuvering speeds.

2.1 One-Degree-of-Freedom Extender

To study the feasibility of human force amplification via hydraulic actuators, a one-degree-of-freedom extender was built (Figure 2). This experimental extender consists of an inner tube and an outer tube. The human arm, wrapped in a cylinder of rubber for a snug fit, is located in the inner tube. A rotary hydraulic actuator, mounted on a solid platform, powers the outer tube of the extender. A piezoelectric load cell, placed between the two tubes, measures the interaction force between the extender and the human arm. Another piezoelectric load cell, placed between the outer tube and the load, measures the interaction force between the extender and the load. Other sensing devices include a tachometer and encoder (with corresponding counter) to measure the angular speed and orientation. A microcomputer is used for data acquisition and control. We developed a stabilizing control algorithm which creates any arbitrary force amplification and filtering. This study led to understanding the nature of extender instability resulting from human-machine interaction (Kazerooni 90b).

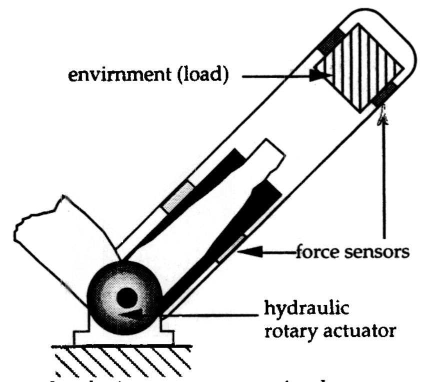


Figure 2: A one-degree-of-freedom hydraulic extender during an unconstrained maneuver.

2.2 Two-Degree-of-Freedom Direct-Drive Electric Extender

To rapidly maneuver light loads (weighing less than 50 lb), the bandwidth of the extender's actuators must be wider than the human largest maneuvering bandwidh. The dynamic behavior of the extender system at high speeds is non-linear. To develop and test nonlinear control algorithms, a direct-drive, electrically-powered extender was built (Figure 3). The direct connection of the motors to the links (without any transmission systems) produces highly nonlinear behavior in the extender. This extender has two degrees of freedom corresponding to a shoulder and an elbow. Two motors are located at the same height as the average human shoulder. Force sensors are located at the human-extender and extender-load interfaces. A third degree of freedom may be added: either rotation about a vertical axis or roll about a horizontal fore-aft axis. Figure 3 shows the seven-bar-linkage mechanism used for our prototype laboratory system. Force sensors are mounted at the human-machine and machine-environment interfaces. Motor 2 rotates link 4 causing the main arm (link 6) to move up and down via a four-bar linkage (links 4, 5, 6, and 3 as the ground link). In another four-bar linkage (links 1, 2, 3, and 7), motor 1 rotates link 1 causing the follower link (link 3) and the main arm (link 6) to move in and out. Both motors 1 and 2 are connected to bracket 7 which is mounted on a platform at the same height as the human shoulder. A gripper is mounted on link 6 where the operator force, is measured along two directions. When the human holds onto the gripper, his/her upper arm parallels link 3 and his lower arm parallels link 6. The materials and the dimensions of the device components are chosen to preserve the structural-dynamic integrity of the haptic interface. Each link is machined as one solid piece rather than as an assembly of smaller parts. Link 1, 3, 6 are made of high strength 7075 aluminum alloy to reduce the weight of the haptic interface device. Link 2, 4, 5 are made of steel to fit in limited design space. This study led to understanding the nonlinear stability analysis and the trade-offs between stability and performance for extenders with nonlinear behavior (Kazerooni and Her 94).

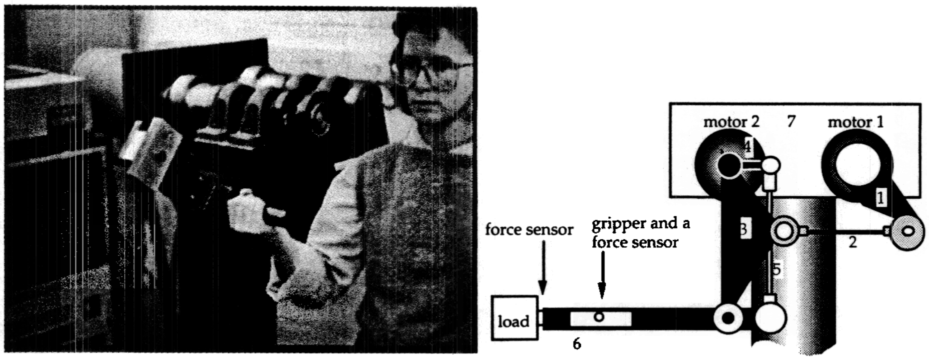


Figure 3: A two-degree-of-freedom direct-drive experimental extender to verify the feasibility of using direct-drive actuators for high-speed maneuvers of loads weighing less than 50 lb.

2.3 A Two-Degree-of-Freedom Non-Direct-Drive System to Measure Human Arm Dynamics

We have learned from our research work that human arm dynamic behavior is the dynamic element which varies the most in human-machine systems, both from person to person and also within one person. To understand significant variations in human arm dynamics when the human wears an extender, a computer-driven XY table was designed and built for measuring the human arm dynamics in horizontal maneuvers (Figure 4). A piezoelectric force sensor between the handle and the table measures the human's force along two orthogonal directions. Two high-resolution encoders on the motors measure the table's motion to within two microns. In a set of experiments where the table was maneuvered by a computer, the operator tried to move her hand and follow the table so that zero contact force was created between her hand and the table. Since the human arm cannot keep up with the high frequency motion of the table when trying to create zero contact forces, large contact forces would consequently be expected at high frequencies. Based on several experiments, analysis of the power spectral density of the table position and the contact forces resulted in a human arm impedance along two orthogonal horizontal directions (Kazerooni and Mahoney 91).

2.4 Extender Walking Machine

Figure 5 shows one of our experimental walking machines which helped us learn how to control a machine that must stand on its own. This experimental machine has two links which are powered relative to each other by a DC motor. The DC motor is housed in the lower link and it powers the middle joint via a cable and speed. The joint at ground level is not powered: a motor at ground joint would require an prohibitively large and lengthy foot similar to a snow ski. We have developed an actuation mechanism and a control technique which stabilize the mass on top of the second link without the use of any gyro. The control of this *under actuated* dynamic system is the very first and very fundamental issue in the design and control of walking machines for the extender (Pannu, Kazerooni 95).

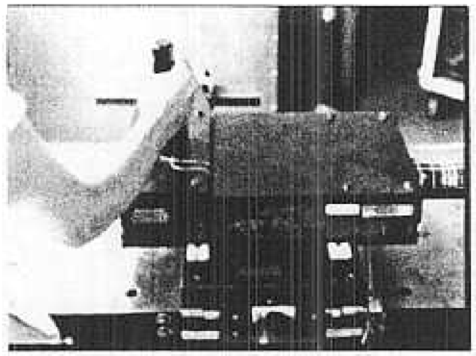


Figure 4: To understand significant variations in human arm dynamics when the human wears an extender, a computer-driven XY table was designed and built for measuring the human arm dynamics in horizontal maneuvers

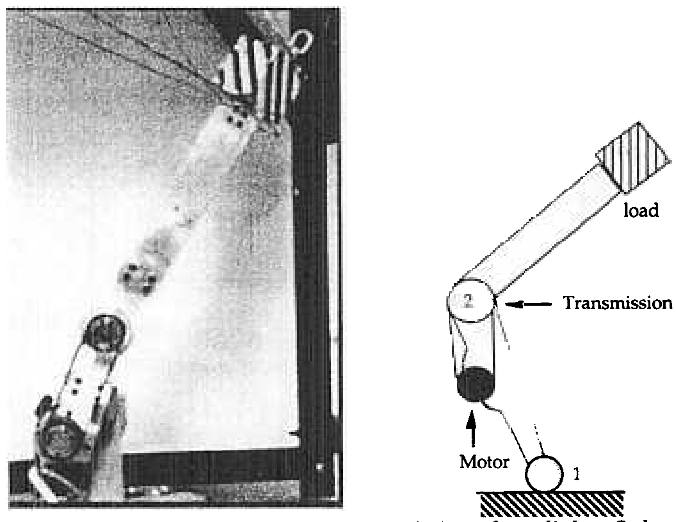


Figure 5: An experimental walking machine consisting of two links. Only one joint is powered. The goal of our research has been to stabilize this under actuated system.

2.5 Hydraulic Industrial Extender

A six-degree-of-freedom hydraulic extender (Figure 1) was designed and built for manipulating heavy objects. The extender's hand linkage performs the grasping function while the arm mechanism executes the load manipulations. The arm mechanism consists of a forearm and an upper arm. The rotational axes of the extender arm are designed to coincide with those of the human arm joints. Both the upper arm and the forearm are planar four-bar linkages. The extender hand mechanism is described in (Kazerooni and Guo 93). Several force sensors, not shown in the figure, are also mounted at the gripper to measure the load force in six directions. The materials and the dimensions of the extender components are chosen to preserve the structural-dynamic integrity of the extender. Each link is machined as one solid piece rather than as an assembly of smaller parts. The links are made of high strength 7075 aluminum alloy to reduce the weight of the extender.

This extender is capable of lifting of objects up to 500 lb when the supply pressure is set at 3000 psi. Since the high frequency maneuvers of 500 lb load is rather unsafe, the experimental analysis on the extender dynamic behavior was carried out at low level of force amplification. In order to observe the system dynamics within the extender bandwidth, in particular the extender instability, the supply pressure was decreased to 800 psi and low force amplification ratios were chosen for analysis. This allows us to maneuver the extender within 2 Hz. Force amplifications of 7 times in the vertical direction and 5 times in the horizontal direction was prescribed on the controller.

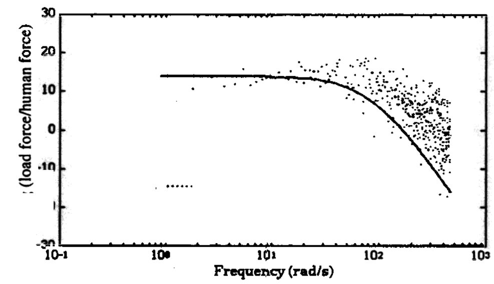


Figure 6: Theoretical and experimental force amplification ratio along the horizontal direction.

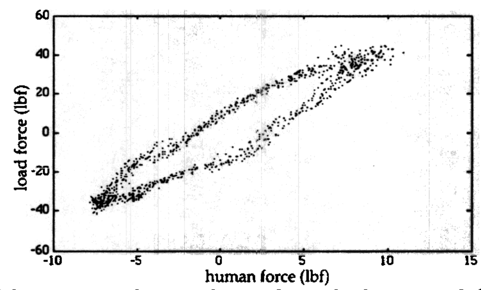
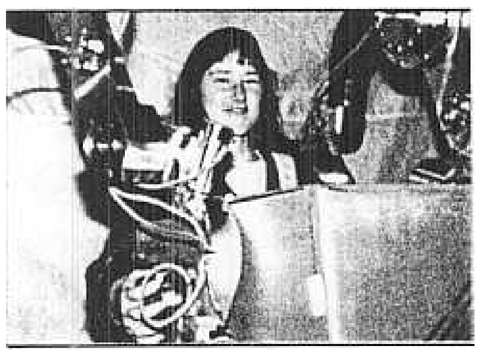


Figure 7: Load force versus human force along the horizontal direction. Slope is approximately 5.

Figure 6 shows the FFT of the ratio of the load force to the human force along the horizontal direction where the load force is more than human force by a factor of 5. It can be seen that this ratio is preserved only within the extender bandwidth. Figure 7 shows the load force versus the human force along the horizontal direction where the slope of -5 represents the force amplification.

2.6 Electric Industrial Extender

The system is composed of two arms and two legs for maneuvering boxes. To verify performance of each subsystem prior to coordination of the entire machine, the arms and legs have been built separately, as shown in Figures 8 and 9. Each arm has five serial joints. An additional "false" degree of freedom exists between the operator's hand and the machine, allowing the operator arbitrary control of his/her hand position and orientation within the allowable work envelope. The first three arm joints are powered by actuators which will be described below. The wrist of the machine is comprised of the remaining two joints, and the "false" degree of freedom previously mentioned. A molded rubber hand piece serves as the interface between the operator and the machine. The wrist joints are unpowered and are arranged in a spherical configuration with the handpiece at the center of their axes. The consequence of this feature is that positioning of a load is accomplished by actuation of the first three powered joints, while orientation of the end effector is achieved through wrist motions powered by the operator. The wrist has been designed to have a degenerate configuration for all possible orientations of the wrist in the targeted work envelope. Such an architecture insures that any loads applied to the end effector will not manifest themselves in moments which must be supported by the operator.



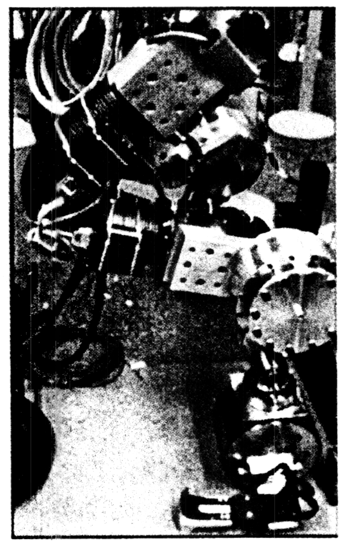


Figure 8. The Electric Arms Maneuvering a Box. The Legs of the Electric Extenders.

In between the elbow and the wrist are two mechanisms for adjustment of the position and orientation of the wrist relative to the rest of the arm. These adjustment mechanisms are included to explore issues of comfort, and are essentially joints that are locked in place during machine operation. A three axis piezoelectric force sensor is mounted in between the rubber hand piece and the end effector. Each leg has four serial degrees of freedom, and in this case, three additional "false" degrees of freedom are used in the interface between the operator and the machine. Similar to the those of the arm, the upper three leg joints are powered. To avoid the use of a long "foot" to support torque at the "ankle" of the machine, there are not any actuators beyond the knee; the final degree of freedom for the leg is the rolling contact that occurs between the ankle and the ground. At the ankle, rotary and linear bearings provide degrees of freedom which are intended to isolate a foot pedal to which the operator's foot is connected through a bicycle cleat. This cleat further allows for rotary motion of the foot from side to side. In between the knee and the ankle are two additional adjustment mechanisms, similar to those of the arms, which alter the position and orientation of the ankle relative to the rest of the leg. A three axis force sensor is mounted in between the foot pedal and the ankle bearing assembly.

The links used in the arms and legs have been constructed from a carbon-composite material formed around a structural foam core. Aluminum inserts bonded to the composite links are used for connecting each link end to its corresponding actuator. The links are curved so as to avoid interference with the operator and the rest of the machine during operation. The legs are controlled based on the technique described in (Pannu and Kazerooni 95)

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