STABILITY AND PERFORMANCE OF HUMAN-ROBOT INTERACTION

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Abstract

A human's ability to perform physical tasks is limited, not by his[1] intelligence, but by his physical strength. If, in an appropriate environment, a machine's mechanical power is closely integrated with a human arm's mechanical power 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 must develop a fundamental solution to the problem of "extending" human mechanical power. The work presented here defines "extenders" 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. This paper gives a summary of the on-going reseasrch work at university of Minnesota on human-machine interaction in the sense of the transfer of power and information signals. The detailed analysis can be found in references 8, 9 and 10.

Concept

The ability of a robot manipulator to perform a task depends upon the available actuator torque: a relatively small hydraulic actuator can supply a large torque. In contrast, the muscular strength of the average human is quite limited. Extenders 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 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. Human-machine interaction in active systems has been traditionally characterized by the exchange of "information signals" only. For example, in human-computer interaction, the human sends information signals to the computer via a keyboard. In another example, a person sends an information signal to an electric mixer by pushing buttons. There is no power transfer between the person and the mixer motor; the person does not feel the load on the mixer motor. 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. A master-slave system (teleoperator system) uses a control joystick of a geometry similar to that of the slave manipulator for input. The joystick (master) has position transducers at the joints to measure displacement, and the output from these transducers is used as an input to the manipulator (slave). Thus, the motion of the manipulator follows that of the joystick. Ideally, the motion of the slave will be identical to that of the master. In contrast, 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 elimination of force feedback in remote master-slave manipulation may result in poor positioning precision and possible instability.

The input to the extender is derived from the contact forces between the extender and the human. The contact force is measured, appropriately modified (in the sense of control theory to satisfy performance and stability criteria), and used as an input to the extender control, in addition to being used for actual maneuvering. Because force reflection occurs naturally in the extender, the human arm feels a scaled-down version of the actual forces on the extender without a separate set of actuators. For example, if an extender is

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

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.

History and Background

The concept of a device to increase the strength of a human operator using a master-slave system has existed since the early 1960s and was originally named "man-amplifier". The man-amplifier was defined as a manipulator which would greatly increase the strength of a human operator while maintaining human control of the manipulator. Note that these early systems were based upon the master-slave concept rather than upon direct physical contact between human and manipulator.

In the early 1960s, the Department of Defense was interested in developing a powered "suit of armor" to augment the lifting and carrying capabilities of soldiers. The original intent was to develop a system which would allow the human operator to walk and to manipulate very heavy objects. In 1962, research was done for the Air Force at the Cornell Aeronautical Laboratory to determine the feasibility of developing a master-slave system to accomplish this task [2]. This study determined that duplicating all human motions would not be practical, and that further experimentation would be required to determine which motions were necessary. It was also determined that the most difficult problems in designing the man-amplifier were in the areas of servo, sensor, and mechanical design.

The Cornell Aeronautical Laboratory did further work on the man-amplifier concept [12] and determined that an exoskeleton (an external structure in the shape of the human body), having far fewer degrees of freedom than the human operator, would be sufficient for most desired tasks. A preliminary arm and shoulder design, developed at Cornell in 1964, determined that the physical size of the hydraulic actuators limited the manipulator's amplifying ability.

Further work on the human-amplifier concept, through prototype development and testing, was carried out at General Electric from 1966 to 1971 [4, 5, 6, 11, 13, 14]. This man-amplifier, known as the Hardiman, was designed as a master-slave system. The Hardiman was a set of overlapping exoskeletons worn by the human operator. The master portion was the inner exoskeleton which followed all the motions of the operator. The outer exoskeleton consisted of a hydraulically actuated slave which followed all the motions of the master. Thus, the slave exoskeleton also followed the motions of the operator.

In contrast with the Hardiman and other man-amplifiers, the extender is not a master-slave system. 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 an object. The extender controller translates the signals representing the interaction force into a motion command for the extender. Thus, the human initiates tracking commands to the extender in a natural way. The controller also regulates the interaction force to be a desired force reflection on the human. The human operator can feel the scaled-down effect of loads and/or interaction forces on the extender because the forces acting on the extender are reflected back naturally.

Some major areas of application for the extender include manufacturing, construction, loading and unloading aircraft, maneuvering cargo in shipyards, foundries, mining, or any situation which requires precise and complex movement of heavy objects. In contrast with existing systems, such as forklifts, pulleys, and cranes, the extender lets the human adjust the orientation of objects. Due to the natural communication between the human and the extender, the extender has major advantages over conventional methods of manipulating heavy objects:

1) The human needs very little training to operate the extender in contrast with driving a system via keyboards and joysticks.

2) The human can react quickly to provide an input to the extender because the forces acting on the extender are fed back naturally. For example, the operator can orient a heavy object faster with an extender.

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

4) The operator can maneuver heavy objects much more naturally. For example, if an object is falling, the operator can prevent the fall more quickly.

The extender also can serve as an upper limb orthosis, enhancing existing motor ability in the physically impaired. An orthosis is an externally applied device which improves the functionality of an impaired limb, in contrast with a prosthesis, which replaces body segments [1, 15]. The extender orthosis would augment the lifting ability of the patient and also allow continued use of the patient's remaining motor ability. To employ the extender, the patient must have some ability to move his arm and thus to drive the extender. The extender would serve to improve the patient's limb function while utilizing the remaining natural limb function. Instead of promoting muscle atrophy, the extender system could be therapeutic and promote further muscle development in the limb.

The first tests on a motor-controlled upper limb orthosis were carried out in 1956 [1] . This was a myoelectric system, which used the electrical output of contracting muscles as a control input. Striated muscles drive body segments and are composed of many motor units. When a striated motor unit is contracted, an electrical signal is generated by the depolarization which initiates the contraction. The sum of the depolarizations from all motor units in the muscle is known as an electromyographic or EMG signal. One disadvantage of using EMG signals is cross talk from other contracting muscles in the region of interest, which may interfere with the desired input. In addition, the signal obtained from the muscles is very small, and thus, noise may be a serious problem. Also, considerable concentration is required to perform manipulation with more than one degree of freedom; this has a serious effect on patient acceptance of the device.

A second alternative for command generation is the mechanical input system. Mechanical input systems rely on a joystick or other input device to initiate a control command. The orthosis follows the motion of the joystick: up-down, left-right, or backward-forward. A disadvantage of this system is coupling of the joystick motion with the orthosis motion. A third alternative for command generation is the photoelectric system, which converts light energy to electric energy for use as a command signal. Such a system requires a light source which can be manipulated by the patient and photo cells to convert energy [3].

Stability and Performance

General models for the human, the extender, and the interaction between the human and the extender are developed for extender control. Considering the extender as a mechanism composed of rigid members, the dynamic behavior of an open-loop extender (without any control feedback) can be derived by a set of nonlinear differential equations via the Lagrangian [7] or Eulerian approaches. However, the rigid body dynamics are not sufficient for modeling if there are other significant dynamic components in the system. For example, if hydraulic actuators are chosen to power the extender, then the dynamic behavior of the actuators may be a considerable factor which must be integrated into the total dynamic behavior of the extender. Transmission systems, when used to drive the extender, may also contribute to the extender dynamics. Therefore, the objective here is to develop an unstructured dynamic model [10] that can represent the complete dynamic behavior of the extender in a very general form. This unstructured model focuses on the relationship between the input and output properties of the extender, and thereby, implicitly includes all of the extender components' dynamics. Structured dynamic models, such as first or second order transfer functions that represent the dynamic behavior of the extender components (e.g., actuators or sensors), are thus avoided in the extender general analysis. These models, when used for control analysis, lead to very specific stability conditions that may not be applicable to all classes of extenders.

The dynamic behavior of the human arm is also expressed as a relationship between inputs and outputs. Therefore, there is less concern for the internal structure of the components in the model. The particular dynamics of nerve conduction, muscle contraction, and central nervous system processing are implicitly accounted for in constructing the dynamic model of the human arm.

What dynamic behavior should the extender have in performing a task? The performance specification does not assure the stability of the system but does let designers express what they wish to have happen during a maneuver if instability does not occur. It is shown 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 the scaled-down values of the forces on the extender: that is, the human has a natural sensation of the forces required to maneuver the load. In other words, the human would feel the scaled-down values of 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 such that a desired relationship is guaranteed between the human force and the environmental force. In another example, 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. Several mathematical expressions are defined to quantify the extender performance specifications.

A sufficient condition for stability of the closed-loop system is developed by the Small Gain Theorem. This sufficient condition results in a class of compensators which guarantee the stability of the system of human, extender and environment taken as a whole. Note that this stability condition 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. A single-degree-of-freedom extender is used to verify experimentally the theoretical predictions for extender stability and performance. This experimental extender consists of an outer tube 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. Another piezoelectric force cell, set between the extender and the environment, measures the interaction force between the extender and environment. 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. The trade-off between stability and performance is illustrated experimentally: the better the required performance (larger force amplification in the experiment), the narrower the stability range is.

Summary

Extenders amplify the strength of the human operator, while utilizing the intelligence of the operator to spontaneously generate the command signal to the system. 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 human-machine interaction in the sense of the transfer of power and information signals. 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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