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The Berkeley Lower Extremity Exoskeleton Project

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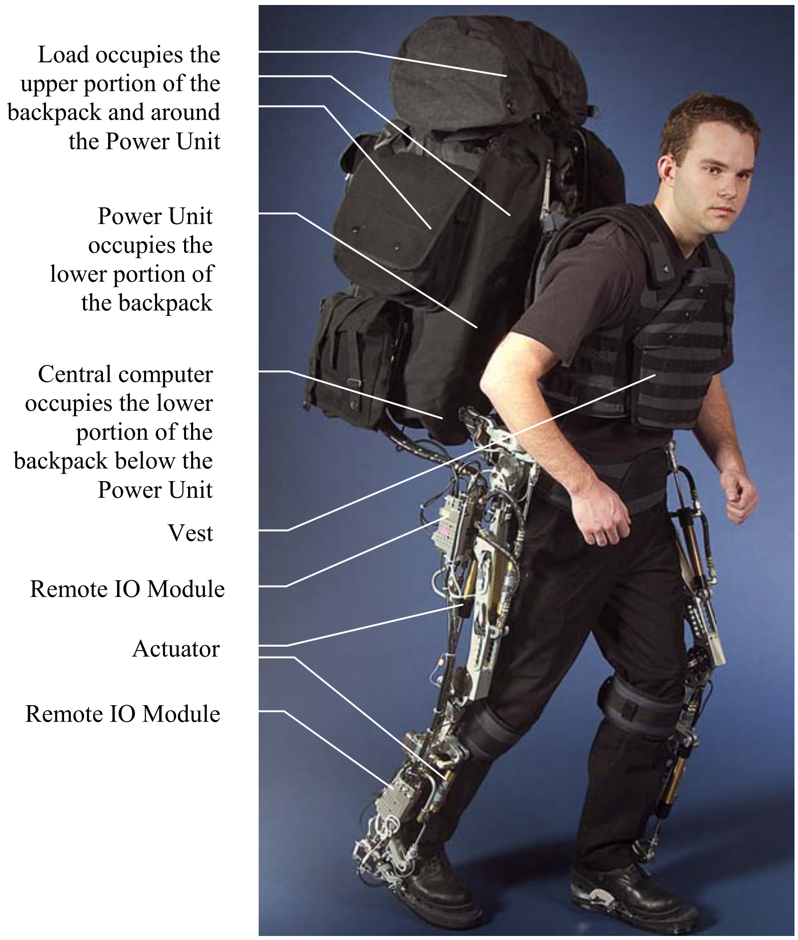
Abstract. In October 2003, the first functional load-bearing and energetically autonomous exoskeleton was demonstrated at Berkeley, walking at the average speed of two miles per hour while carrying 75 pounds of load. DARPA funded the Berkeley Lower Extremity Exoskeleton (BLEEX) project in 2000 at Berkeley. In general, four fundamental technologies were tackled during the course of this project. These four core technologies include the exoskeleton architectural design, control algorithm, a body LAN to host the control algorithm and an on-board power unit to power the actuators, sensors and the computers. This article gives an overview of this project.

1 Introduction

The primary objective of the BLEEX project at U.C. Berkeley was to design, construct and demonstrate a Lower Extremity Exoskeleton for strength and endurance enhancement of humans. The BLEEX provides a wearer with the ability to carry significant loads with minimal effort over any type of terrain for extended periods of time. In October 2003, U.C. Berkeley's Human Engineering and Robotics Laboratory successfully demonstrated the first experimental Exoskeleton in which the pilot (i.e., the wearer) could carry a heavy load, while feeling only a few-pound load. The first prototype experimental exoskeleton is comprised of two powered anthropomorphic legs, a power unit, and a backpack-like frame on which a variety of loads can be mounted. The device connects rigidly to the pilot at the foot and, in order to prevent abrasion, more compliantly elsewhere. The Exoskeleton allows a person to comfortably squat, bend, swing from side to side, twist, walk and run on ascending and descending slopes, and step over and under obstructions while carrying equipment and supplies. While wearing the exoskeleton, the wearer can carry significant loads over considerable distances without reducing his/her agility, thus significantly increasing his/her physical effectiveness. In order to address issues of field robustness and reliability, the system is designed such that, should the exoskeleton lose power (e.g., from fuel exhaustion), the exoskeleton legs can be removed with the device becoming no more than a standard backpack. BLEEX is ergonomic, highly maneuverable, mechanically robust, lightweight and durable.

The Berkeley exoskeleton system provides soldiers, disaster relief workers, wildfire fighters, and other emergency personnel the ability to carry major loads such as food, rescue equipment, first-aid supplies, communications gear and weaponry with minimal effort over any type of terrain for extended periods of time. It is our vision that the BLEEX will provide a versatile transport platform for mission-critical equipment.



The first prototype of Berkeley Lower Extremity Exoskeleton (BLEEX)

2 Related work

In the early 1960s, the Defense Department wanted a man-amplifier, a "powered suit of armor" which would augment soldiers' lifting and carrying capabilities. In 1962, the Air Force had the Cornell Aeronautical Laboratory study the feasibility of using a master-slave robotic system as a man-amplifier. In later work, Cornell determined that an exoskeleton, an external structure in the shape of the human body, with far fewer degrees of freedom than a human, could accomplish most desired tasks [1]. From 1960 to 1971, General Electric developed and tested a prototype man-amplifier, a master-slave system called the Hardiman [2-6]. The Hardiman was a set of overlapping exoskeletons worn by a human operator. The outer exoskeleton (the slave) followed the motions of the inner exoskeleton (the master), which followed the motions of the human operator. All these studies found that duplicating every human motion and using master-slave systems were not practical.

In the mid-1980s Kazerooni, at U.C. Berkeley, initiated several research projects on a new class of upper extremity exoskeleton systems that was referred to human extenders [7-12]. These systems were designed primarily based on compliance control [13-14] scheme that relied on measurement of the interaction force between the human and the machine. Various experimental systems were designed to verify the theories. A hydraulic loader was designed and built for loading aircrafts. An electric power extender was designed and built for two-handed operation. More can be found in http://bleex.me.berkeley.edu

3 Design

The design of the Lower Extremity Exoskeleton differs from the design of conventional automated robotic systems since the device interfaces with its pilot on a physical level. The exoskeleton must be designed to have the same workspace of the pilot while not interfering with his motion. The exoskeleton can be either anthropomorphic (i.e., kinematically matching), or non-anthropomorphic (i.e. kinematically matching the operator only at the connection points between human and machine). The anthropomorphic architecture was selected because it is the architecture most transparent to the pilot. We also learned through our past experience that an exoskeleton that kinematically matches the wearer's legs gains the most acceptances by the wearer and in addition, is safer to wear. Consequently, the exoskeleton was designed to have the same degrees of freedom of the pilot: three degrees of freedom at the ankle and hip, and one degree of freedom at the knee. This architecture also allowed the appropriately scaled clinical human walking data to be employed for design of the exoskeleton components including the workspace, actuators and the power source.

A study of clinical gait analysis (CGA) data provides evidence that humans expend the most power through the sagittal plane joints of the ankle, knee, and hip while walking, squatting, climbing stairs, and most other common maneuvers. For this reason, the sagittal plane joints of the first prototype exoskeleton are hydraulically powered. However, to save power, the non-sagittal degrees of freedom at the ankle and hip remain un-powered. This forces the pilot to provide the force to maneuver the exoskeleton abduction and rotation, where the forces are smaller. To further reduce the burden on the human operator, even the un-actuated degrees of freedom are spring-loaded to a neutral standing position. Using CGA data and human factors information, the ranges of motion were selected to be larger than those of the human while walking, and smaller than the physical limit of the human joints. This ensures sufficient flexibility for walking, while maintaining the safety of the pilot. In order to accommodate the largest number of wearers, the exoskeleton was designed to have adjustable shank and thigh sections. These sections will adjust from 5% to 95% of the shank and thigh length of men in the U.S. Army as determined from the human factors book. At the foot, the exoskeleton rigidly attaches to the wearer's boot with a binding. A flexible toe-section, ankle abduction, and vertical rotation axis allow the foot of the device sufficient maneuverability to keep from encumbering the human.

The hips connect the legs to the torso through three degrees of freedom. The exoskeleton torso is a structural member that rigidly connects to the pilot vest. The vest is designed from small hard surfaces (Polycarbonate), connected compliantly together, to conform to the pilot's chest, shoulders and upper back, ensuring a large area of contact with the pilot. This prevents concentrated forces between the exo and the wearer. The torso also provides mounting points for the power supply, payload and computer.

A thorough analysis of Clinical Gait Analysis (CGA) data was used to provide the basis for the exoskeleton actuation design. The ankle actuators were designed to provide relatively large plantarflexion torques (~1000 lb-in), corresponding to those needed for propulsion at toe-off. The knee actuators were designed to provide both large extension torques (~800 lb-in) needed during heel strike, while walking, and large flexion torques (~-800 lb-in) needed during swing, while climbing stairs. The hip actuators were designed to provide relatively symmetric flexion and extension torques (+/- 900 lb-in), corresponding to the symmetric nature of the torques required to walk. These critical design decisions were further verified by physiological observation.

4 Electronics

The exoskeleton electronics (EXOLINK) was designed to simplify and reduce the cabling task of all the sensors and actuators needed for the exoskeleton control. The exoskeleton control code resides on a body LAN (local area network). The electronics platform uses a high-speed synchronous ring network topology where several electronic Remote Input Output Modules (RIOM) can reside in a ring. Each RIOM is in communication with several sensors and one actuator in close proximity. Each RIOM includes eight sixteen-bit Analog-to-Digital Converters (ADC), two quadrature counters, eight bits of digital input and output ports, two Digital-to-Analogue Converter (DAC) and analog filters. Each RIOM includes localized power regulation and isolation to minimize signal noise and system ground loops. Each RIOM is designed with a FPGA to manage all

RIOM data transaction and filtering. The data gathered by each module is encoded and transmitted digitally to a central computer through the ring.

The EXOLINK have four rings, in which two of the rings (associated with two legs) include three modules. The third ring is interfaced to a Graphical User Interface for debugging and data acquisition. The fourth ring is used to accommodate to other electronic and communication gears that are not related to the exoskeleton, but which the pilot must carry. Each ring can accommodate up to eight RIOMs.

The EXOLINK consists of a microcomputer and a Supervisor IO Module (SIOM). The SIOM includes a FPGA programmed to serve as the communication hub for all four rings. A current transceiver chip residing in the SIOM and all the RIOMs allows for data transfer at a rate of 1500 Mb/s. Currently, a 650 MHz Pentium PC-104 microcomputer is used to implement the control algorithm. The current Exoskeleton utilizes 75% of the I/O capability of the EXOLINK. The use of a high-speed synchronous network in place of the tradition parallel method enables the exoskeleton to reduce the over 200 sensor and actuator wires to only 24 communication and power wires. While the sensors are read at the rate of 10KHtz, the control is updated at the arte of 4KHtz (Control sampling time is 250 micro-seconds).

5 Control

The design of the Berkeley exoskeleton benefits from the advantage of human intellect and the strength advantage of the exoskeleton: the human provides an intelligent control system for the exoskeleton, while the exoskeleton's actuators provide most of the strength necessary for performing the task. There is no joystick, pushbutton, or keyboard to “drive” the device; the pilot becomes an integral part of the exoskeleton while walking, with the exoskeleton carrying the majority of the load. The control algorithm ensures that the exoskeleton moves in concert with the pilot with minimal interaction force between the two. The control scheme needs no direct measurements from the human or from the human-machine interface (e.g., force sensors between them). The controller, based on measurements from the exoskeleton only, estimates (i.e., computes very quickly) how to move so that the wearer feels very few forces. This novel and unprecedented control scheme is quite elaborate, has never been applied to any other robotic system, but is an effective way to create locomotion for the exoskeleton when the area of contact between the wearer and the machine is unpredictable. The control method is superior to compliance control methods described in references because it requires no force sensor between the wearer and the exoskeleton.

6 Power Source

One of the primary bottlenecks in achieving energetic autonomy with mobile robots is the power supply. Every effort was made to ensure that the BLEEX is energetically autonomous and is field re-fuelable. Current mobile robotic devices typically use a tether connecting the robot to a large stationary power supply, or carry large numbers of batteries for relatively short operation times. A significant challenge in the design of the Berkeley lower extremity exoskeleton was the development of a power supply and actuation system that would satisfy its power and energy requirements for a long mission.

We see an exoskeleton as a mobile fieldable platform just like a vehicle or a motorcycle. We do not observe an exoskeleton as simply an indoor industrial robot that uses electric power through a power cord to energize its limbs. This paradigm shift on exoskeleton design forces us to confront a set of design questions (including the power source) right at the beginning stage of design. Hydrocarbon fuels in the form of gasoline or diesel fuel are the most suitable form of energy due to their large specific energy (45 Mega Jules per Kilogram) for mobile platforms. Electric motor actuators, common in industrial robotics due to their simplicity and convenience, have a low specific power, resulting in heavy and bulky actuation systems that require large power sources.

The Berkeley exoskeleton uses a state-of-the-art small Hydraulic Power Unit (HPU), which delivers hydraulic power for locomotion and electrical power for the computer and sensors. The hybrid power source is capable of powering a human scale mobile robotic system for a period of hours, rather than minutes, free from external tethers. This form of HPU combines the high specific energy of hydrocarbon fuels with the high specific power of hydraulic actuator systems. We designed two HPUs to accommodate different power for the exoskeleton. The first design consists of an air-cooled four-stroke single cylinder gasoline engine coupled to a three-phase brushless generator and a hydraulic gear pump for powering electronics as well as hydraulic actuators. This HPU provides 0.78 KW (1.04 HP) of hydraulic power at a 6.9 MPa operating pressure (i.e., 1.8 GPM of hydraulic flow at 1000 psi), as well as approximately 200 W of electrical power. The small flow of this HPU constrains the walking speed of the exoskeleton to 2 miles per hour. A one-gallon fuel tank provides approximately 2.25 hours of run time, which translates into approximately 4.5 miles.

A more powerful HPU was designed for faster walking. This HPU consists of a liquid-cooled, two-stroke opposed cylinder gasoline engine directly coupled to a three-phase brushless generator and a hydraulic gear pump for powering electronics as well as hydraulic actuators. In order to minimize mass and facilitate tight packaging with limited cooling airflow, the HPU is liquid-cooled with the same hydraulic fluid that the actuators utilize. This HPU successfully produces 2.24 KW (3 HP) of hydraulic power at a 6.9 MPa operating pressure (i.e., 5.2 GPM of hydraulic flow at 1000 psi), as well as 300 W of electrical power. The larger flow of this HPU allows the walking speed of the exoskeleton to exceed 4 miles per hour (limited by control bandwidth). A one-gallon fuel tank provides approximately 1 hour of run time, which translates into

4.5 miles of travel. Basically, the second HPU decreases the mission time by approximately half for a given distance and payload. Each HPU weighs about 35 lbs. The noise level produced by both HPUs is minimized using a novel exhaust system and integrated baffling incorporated in the system packaging. The controllers of the HPUs regulate two variables: the hydraulic pressure and the engine, speed employing two inputs: engine throttle and a hydraulic valve.

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