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The Berkeley Lower Extremity Exoskeleton Project

That which does not stabilize will only make us stronger

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Abstract. In October 2003, the first functional load-bearing and energetically autonomous exoskeleton, called the Berkeley Lower Extremity Exoskeleton (BLEEX) was demonstrated, walking at the average speed of two miles per hour while carrying 75 pounds of load. The project, funded in 2000 by the Defense Advanced Research Project Agency (DARPA) tackled four fundamental technologies: the exoskeleton architectural design, a 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 the BLEEX project.

1   What is a Lower Extremity Exoskeleton?

The primary objective of this project at U.C. Berkeley is to develop the fundamental technologies associated with design and control of energetically autonomous Lower Extremity Exoskeletons that augment human strength and endurance during locomotion. The first field-operational lower extremity exoskeleton at Berkeley (commonly referred to as BLEEX) is comprised of two powered anthropomorphic legs, a power unit, and a backpack-like frame on which a variety of heavy loads can be mounted. This system provides its pilot (i.e., its wearer) the ability to carry significant loads on his/her back with minimal effort over any type of terrain. BLEEX allows the pilot to comfortably squat, bend, swing from side to side, twist, and walk on ascending and descending slopes, while also offering the ability to step over and under obstructions while carrying equipment and supplies. Because the pilot can carry significant loads for extended periods of time without reducing his/her agility, physical effectiveness increases significantly with the aid of this class of lower extremity exoskeletons. In order to address issues of field robustness and reliability, BLEEX is designed such that, in the case of power loss (e.g., from fuel exhaustion), the exoskeleton legs can be easily removed and the remainder of the device can be carried like a standard backpack.

BLEEX was first unveiled in October 2003, at U.C. Berkeley's Human Engineering and Robotics Laboratory. In this initial model, BLEEX offered a carrying capacity of seventy five pounds, with weight in excess of that allowance being supported by the pilot.

BLEEX's unique design offers an ergonomic, highly maneuverable, mechanically robust, lightweight, and durable outfit to surpass typical human limitations. BLEEX has numerous applications; it can provide 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 without the strain typically associated with demanding labor. It is our vision that BLEEX will provide a versatile transport platform for mission-critical equipment.

Load occupies the upper portion of the backpack and around the Power Unit

Power Unit occupies the lower portion of the backpack

Central computer occupies the lower portion of the backpack below the Power Unit

Vest

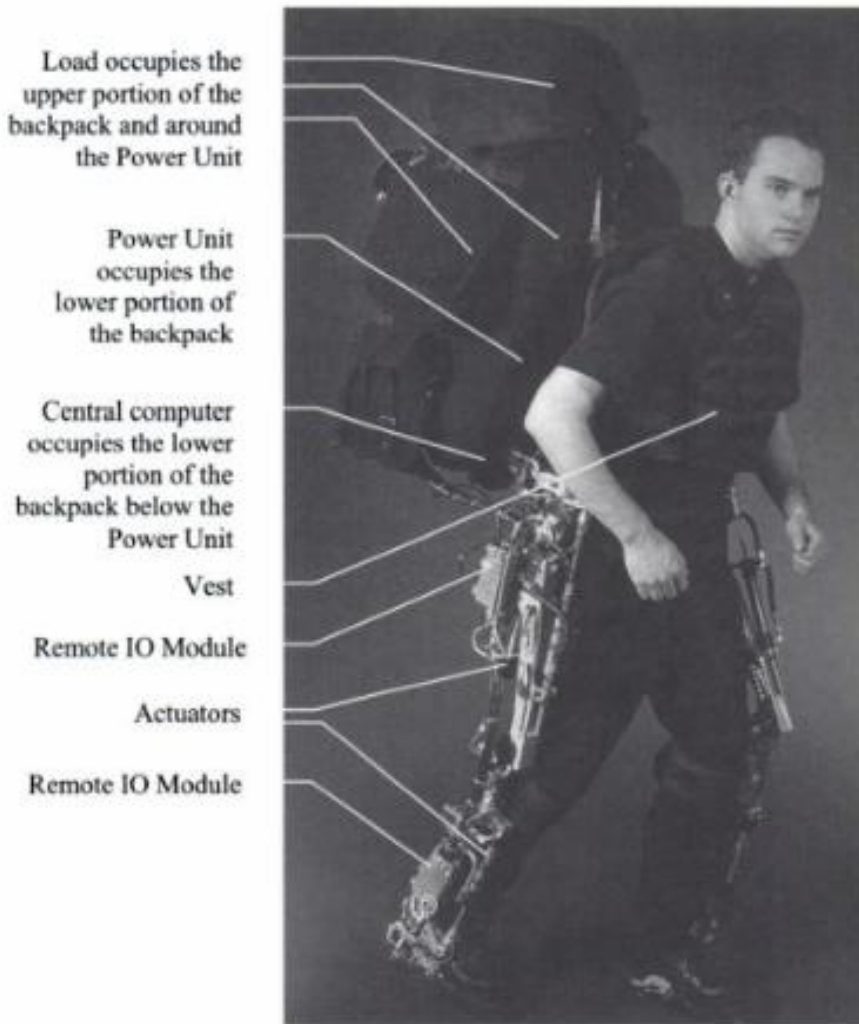Remote IO Module

Actuators

Remote IO Module

Figure 1: Berkeley Lower Extremity Exoskeleton (BLEEX)

2 Disconnection of Lower Extremity and Upper Extremity Augmentation

Human-Robot integration, in particular human augmentation, outlines the future of robotics. Although autonomous robotic systems perform remarkably in structured environments (e.g. factories), integrated human-robotic systems are superior to any autonomous robotic systems in unstructured environments that demand significant adaptation. In our research work at Berkeley, we have separated the technology associated with human power augmentation into lower extremity exoskeletons and upper extremity exoskeletons. The reason for this was two-fold; firstly, we could envision a great many applications for either a stand-alone lower or upper extremity exoskeleton in the immediate future. Secondly, and more importantly for the division is that the exoskeletons are in their early stages, and further research still needs to be conducted to ensure that the upper extremity exoskeleton and lower extremity exoskeleton can function well independently before we can venture an attempt to integrate them. With this in mind, we proceeded with the designs of the lower and upper extremity exoskeleton separately, with little concern for the development of an integrated exoskeleton. We will first give a summary of the upper extremity exoskeleton efforts at Berkeley and then we will proceed with the description of the BLEEX project.

3 What is an Upper Extremity Exoskeleton?

In the mid-1980s, we initiated several research projects on upper extremity exoskeleton systems, billed as "human extenders [1-5]." The main function of an upper extremity exoskeleton is human power augmentation for manipulation of heavy and bulky objects. These systems, which are also known as assist devices or human power extenders, can simulate forces on a worker's arms and torso. These forces differ from, and are usually much less than the forces needed to maneuver a load. When a worker uses an upper extremity exoskeleton to move a load, the device bears the bulk of the weight by itself, while transferring to the user as a natural feedback, a scaled-down value of the load's actual weight. For example, for every 40 pounds of weight from an object, a worker might support only 4 pounds while the device supports the remaining 36 pounds. In this fashion, the worker can still sense the load's weight and judge his/her movements accordingly, but the force he/she feels is much smaller than what he/she would feel without the device. In another example, suppose the worker uses the device to maneuver a large, rigid, and bulky object, such as an exhaust pipe. The device will convey the force to the worker as if it was a light, single-point mass. This limits the cross-coupled and centrifugal forces that increase the difficulty of maneuvering a rigid body and can sometimes produce injurious forces on the wrist. In a third example, suppose a worker uses the device to handle a powered torque wrench. The device will decrease and filter the forces transferred from the wrench to the worker's arm so the worker feels the low-frequency components of

the wrench's vibratory forces instead of the high-frequency components that produce fatigue.

The assist devices we designed not only filter out unwanted forces on a worker, but can also be programmed to follow a particular trajectory regardless of the exact direction in which the worker attempts to manipulate the device. For example, suppose an auto-assembly worker is using an assist device to move a seat to its final destination inside a car. The assist device can bring the seat to its final destination, moving it along a preprogrammed path with a speed that is proportional to the magnitude of the worker's force on the device. Although the worker might be paying very little attention to the final destination of the seat, the device can still bring the seat to its proper place without the worker's guidance. The upper extremity exoskeleton reflects on the worker's arm forces that are limited and much smaller than the forces needed to maneuver loads.

This interaction between humans and machines benefits from the combination of human intellect and machine strength; the human provides a decision-making system for the assist device, while the device actuators provide most of the strength. With it, auto-assembly and warehouse workers can maneuver parts and boxes with greatly improved dexterity and precision, not to mention a marked decrease in muscle strain. Put into use, these devices will significantly reduce the incidence of back injury in the workplace, which will in turn greatly offset the annual cost of treating back injuries.

Figure 2: Electric Upper Extremity Exoskeleton

Upper extremity exoskeletons were designed based primarily on compliance control [6-8] schemes that relied on the measurement of interaction force between the human and the machine. Various experimental systems, including a hydraulic loader designed for loading aircrafts and an electric power extender built for two-handed operation, were designed to verify the theories. We also developed low-cost industrial upper extremity extenders (commonly referred to as intelligent assist devices) that are now widely used in the US and Europe. An Intelligent Assist Device includes a computer controlled electric actuator which is attached directly to a ceiling, or an overhead crane and precisely moves a wire rope with a controllable speed. Attached to the wire rope is a sensory end-effector where the operator hand, the IAD, and the load come in contact. In these assist devices, the operator force on the device is sensed and amplified electronically by use of a computer to drive the actuator. The end-effector includes a load interface subsystem which is designed to interface with a variety of loads and holding devices such as suction cups and hooks.
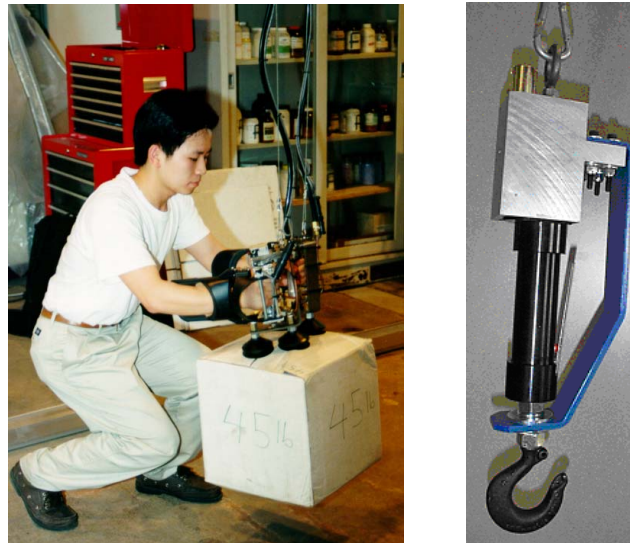
Figure 3: Intelligent Assist Devices (IAD): the simplest form of upper extremity enhancers for industrial applications

4 Highlights of the BLEEX Design

In designing BLEEX, several factors had to be considered: Firstly, the exoskeleton needed to exist in the same workspace of the pilot without interfering with his motion. Secondly, it had to be decided whether the exoskeleton should be anthropomorphic (i.e., kinematically matching), or non-anthropomorphic (i.e. kinematically matching the operator only at the connection points between human

and machine). We ultimately selected the anthropomorphic architecture because of its transparency to the pilot. We also concluded that an exoskeleton that kinematically matches the wearer's legs gains the most psychological acceptance by the user and is therefore safer to wear. Consequently, the exoskeleton was designed to have the same degrees of freedom as the pilot: three degrees at the ankle and the hip, and one degree 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 powered. However, to save energy, the non-sagittal degrees of freedom at the ankle and hip remain unpowered. This compels the pilot to provide the force to maneuver the exoskeleton abduction and rotation, where the required operational forces are smaller. To further reduce the burden on the human operator, the unactuated degrees of freedom are spring-loaded to a neutral standing position. Using CGA data and human factors information, the ranges of motion for the exoskeleton 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 pilots, 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 literature. At the foot, the exoskeleton rigidly attaches to the pilot's boot with a binding, but a flexible toe-section, ankle abduction, and vertical rotation axis allow the exoskeleton foot sufficient maneuverability to keep from encumbering the user.

The hips connect the legs to the torso through three degrees of freedom. Among these three degrees of freedom, only one degree in the sagital plane is powered. The exoskeleton torso is a structural member that rigidly connects to the pilot vest. The vest is designed from several hard Polycarbonate surfaces connected compliantly together to conform to the pilot's chest, shoulders and upper back, thereby preventing concentrated forces between the exoskeleton and the wearer. The torso also provides mounting points for the power supply, payload and computer.

The Clinical Gait Analysis (CGA) was used to provide not only the basis for the exoskeleton kinematics and dynamic architecture, but also for its actuation. The deployment of this CGA data was motivated by the assumption that BLEEX resembles a human's weight and volume. The BLEEX 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, which occurs while walking, and large flexion torques (~-800 lb-in) needed

during swing, which occurs with actions like 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 at the hip to walk. These critical design decisions were further reinforced by physiological observation. Since hydraulic linear actuators were employed to power the BLEEX joints, the imposed torque at each joint was a nonlinear function of the actuator location and its geometry. An optimization code was written to locate both the actuator endpoint locations and the area of the cross section of the actuators so as to yield the right amount of torque at each joint. If the actuators were designed to yield a large amount of torque more than what is prescribed by CGA data at each joint, then there would be a great amount of power loss during modulation (e.g. control).

CGA data, which provided torque and speed information at each joint of a 165 pound person, was also used to size the exoskeleton power source. The information suggested that a typical person uses about 0.25 HP (185 Watts) to walk at average speed of 3 mph. This figure, which represents the average product of speed and torque, is an expression of the purely mechanical power exhibited at the legs during walking. Since we assumed that the exoskeleton is similar to a human in terms of geometry and weight, one of the key design objectives turned out to be designing a power unit and actuation system to deliver about 0.25 HP at the exoskeleton joints.

5 BLEEX Electronics

BLEEX uses a multivariable nonlinear algorithm to robustly control its behavior. The system has many degrees of freedom with a great number of sensors and actuators. Since all computations required to implement the control are conducted on a single computer, we needed a control platform to minimize the number of signal wires in the system. The exoskeleton electronics system, EXOLINK, was designed to simplify and reduce the cabling task of all the sensors and actuators needed for exoskeleton control. It relies on a high-speed synchronous ring network topology where several electronic Remote Input Output Modules (RIOM) reside in a ring. Each RIOM is in communication with several sensors and one actuator in close proximity, and includes eight sixteen-bit Analog-to-Digital Converters (ADC), two quadrature counters, eight bits of digital input and output ports, two Digital-to-Analogue converters (DAC) and analog filters. Each RIOM also includes localized power regulation and isolation to minimize signal noise and system ground loops while a built-in FPGA manages 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 has four rings, two of which are associated with the two legs and include three Remote Input Output Modules. A third ring is connected to a Graphical User Interface for debugging and data acquisition, and a fourth ring is used to accommodate other electronic and communication gears that are not

related to the exoskeleton, but which the pilot must carry. Each ring is equipped to 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 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, and 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 traditional 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 4KHtz (Control sampling time is 250 micro-seconds).

6 BLEEX Control

The effectiveness of the lower extremity exoskeleton stems from the combined benefit of the human intellect provided by the user and the strength advantage offered by the exoskeleton. The human provides an intelligent control system for the exoskeleton, while the exoskeleton actuators provide most of the strength necessary for walking.   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 user or the human-machine interface (e.g. the force sensors between the two); instead, the controller estimates, based on measurements from the exoskeleton only, how to move so that the wearer feels very little force. This novel control scheme, which has never before been applied to any robotic system, is a complex but effective method of generating locomotion when the contact location between the wearer and the machine is unknown and unpredictable (i.e. the exoskeleton and the wearer are in contact in variety of places).   This control method differs from compliance control methods employed for upper extremity exoskeletons because it requires no force sensor between the wearer and the exoskeleton.

The basic principle for the control of BLEEX rests on the notion that the exoskeleton needs to shadow the wearer's voluntary and involuntary movements quickly, and without delay. This means that the exoskeleton requires a high level of sensitivity in response to all forces and torques on the exoskeleton, in particular the forces imposed from the wearer. Addressing this need involves a direct conflict with control science's goal of minimizing system sensitivity in the design of a closed loop feedback system, but the exoskeleton is a system that requires considerable sensitivity to external forces and torques to perform its function properly; if fitted with a low sensitivity, the system will not move in concert with its wearer. We realize, however, that maximizing system sensitivity to external forces and torques leads to a loss of robustness in the system.

Taking into account this new approach, our goal was to develop a control system for BLEEX with high sensitivity. We were faced with two realistic concerns associated with this approach; the first was that an exoskeleton with high sensitivity to external forces would respond to other external forces that are not initiated by its pilot. For example if someone pushed against an exoskeleton that had high sensitivity, the exoskeleton would move just like the way it would move in response to the forces from its pilot. Although this may sound like a serious problem, the fact is we want to ensure that the exoskeleton does not stabilize its behavior on its own in response to other forces. If it did, the pilot would receive motion from the exoskeleton unexpectedly and would have to struggle with it to avoid unwanted movement. The key to stabilizing the exoskeleton and preventing it from falling in response to external forces depends on the pilot's ability to move quickly (e.g. step back or sideways) to create a stable situation for himself and the exoskeleton. For this, a very large control bandwidth is needed so the exoskeleton can respond to both voluntary and involuntary movements (reflexes).

The second concern is that systems with high sensitivity to external forces and torques are not robust to variations and therefore the precision of the system performance will be proportional to the precision of the exoskeleton dynamic model. This is quite a serious drawback and we have accepted it since various experimental systems in our laboratory proved the effectiveness of the control method in shadowing the pilot's movement.

One class of systems that has large sensitivity is marginally stable systems. We therefore designed a marginally stable closed loop controller system that uses the sensor information on the exoskeleton only. This is done by using the inverse of the dynamics of the exoskeleton as a positive feedback controller so the loop gain for the exoskeleton approaches unity (slightly less than 1). Obviously, to get this method working properly, one needs to understand the dynamics of the exoskeleton quite well, as the controller is heavily model based. Our experiments with BLEEX have shown that at this time, this control scheme— which does not stabilize BLEEX— forces it to follow human wide bandwidth maneuvers while carrying heavy loads although it requires a great deal of dynamic modeling. We have come to believe that that which does not stabilize, will only make us stronger.

7   BLEEX Power Unit

One of the greatest hurdles to overcome in achieving energetic autonomy with mobile robots is the power supply. Every effort has been made to ensure that BLEEX is energetically autonomous and field re-fuelable. Current mobile robotic devices typically use a tether attaching the robot to a large stationary power supply, or they carry large numbers of batteries for relatively short operation times. A significant challenge in designing the Berkeley lower extremity exoskeleton was the development of a power supply and actuation system that would satisfy its power and energy requirements for an extended amount of time.

We view the exoskeleton as a mobile fieldable platform like a vehicle or motorcycle, rather than an indoor industrial robot with 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) at the initial stages of design. Hydrocarbon fuels in the form of gasoline or diesel fuel are the most suitable form of energy for mobile platforms, due to their large specific energy (45 Mega Jules per Kilogram). Electric motor actuators, common in industrial robotics due to their simplicity and convenience, have a low power density, resulting in heavy and bulky actuation systems that require large power sources for long term missions.

BLEEX uses a specially-designed Hydraulic Power Unit (HPU), which delivers hydraulic power for locomotion and electrical power for the computing components and sensors. This hybrid power system is capable of fueling an otherwise unpowered human scale mobile robotic system for a period of hours, rather than minutes, and combines the high specific energy of hydrocarbon fuels with the high specific power of hydraulic actuator systems. According to CGA data, we found that a 165 pound person uses 0.25 HP of mechanical power to walk with the speed of 3 MPH. The key issue is to design a power and actuation system to deliver about 0.25 HP at the exoskeleton joints, assuming the exoskeleton resembles a 165 lb. person. The power unit should also provide about 150W of electrical power to fuel the electronic systems, including the computer, RIOMs and sensors. According to a detailed set of calculations, it was concluded that an exoskeleton that resembles a 165 lb. person and uses hydraulic for actuation needs a 1.6 HP hydraulic power supply (2.7GPM of hydraulic flow at 1000 psi) to walk the exoskeleton at the speed of 3MPH. We designed two HPUs to accommodate two different power sources for the exoskeleton.

The first design consists of an air-cooled four-stroke single cylinder engine coupled to a three-phase brushless generator and a hydraulic pump for powering electronics as well as hydraulic actuators. This HPU was capable of producing a maximum of 1.4 HP (1.04 KW) of hydraulic power at 1000 psi (6.9 MPa) operating pressure (i.e., 2.4 GPM of hydraulic flow), as well as approximately 200 W of electrical power. We carried out a set of experiments with the exo and we learned that this HPU produces 1.08 HP and 1.4 HP at walking speeds of 1.3 MPH and 1.9 MPH. The actual mechanical power used for two locomotion speeds were 0.24 HP and 0.31 HP, compared to 0.25 HP for a human walking at the speed of 3 MPH. We were never able to walk with the speed of 3 MPH with the BLEEX as the power unit saturated; the inadequate power (i.e. inadequate flow since pressure was regulated to 1000 psi) of this HPU limits the walking speed of the exoskeleton to 1.9 MPH. Although, the power draw from the exoskeleton power unit was in the same order of magnitude of the estimated one, the discrepancy was due to the fact that BLEEX's stature turned out not to be exactly like that of a person in term of weight and geometry. For example the load on the exoskeleton's back made it rather dissimilar to a person. We also realized that a one-gallon fuel tank provides approximately 4 hours of run time, which results in approximately 8 miles of travel distance. This long distance for a mission could not be achieved using batteries.

For faster walking (not longer mission times), we designed a HPU with more power. 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 3HP (2.24 KW) of hydraulic power at a 1000 psi (6.9 MPa) operating pressure (i.e., 5.2 GPM of hydraulic flow), in addition to 300 W of electrical power. The larger flow of this HPU theoretically allows the walking speed of the exoskeleton to exceed 4 MPH, but this speed is in practice limited by control bandwidth. A one-gallon fuel tank provides approximately 1 hour and 15 minutes of mission time at its maximum power (5.2 GPM at 1000 psi), which translates into 5 miles of travel in one hour. We concluded that this second HPU decreases the mission time by half for a given distance and payload.

The controllers of the HPUs regulate two variables: the hydraulic pressure and the engine speed employing two inputs: engine throttle and a bypass hydraulic valve. The hydraulic pressure was regulated at 1000 psi and the speed was regulated at a speed that the hydraulic pump or the engine had their highest efficiency and peak power (7000 RPM for the first HPU and 6500RPM for the second HPU). The constant engine speed also led to the design of an optimized muffler. The noise level produced by both HPUs is minimized using an exhaust system and integrated baffling incorporated in the system packaging.

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