Hybrid Hydraulic-Electric Power Unit for Field and Service Robots

Kurt Amundson, Justin Raade, Nathan Harding, and H. Kazerooni
Department of Mechanical Engineering
University of California, Berkeley, California, 94720, USA
exo@berkeley.edu, http://bleex.me.berkeley.edu

Abstract - **Energetic autonomy of a hydraulic-based mobile field robot requires a power source capable of both electrical and hydraulic power generation. While the hydraulic power is used for locomotion, the electric power is used for the computer, sensors and other peripherals. An internal combustion engine was used as the prime mover due to the high energy density of gasoline. The primary specification for this hybrid Hydraulic-Electric Power Unit (HEPU) is that it must output *constant pressure hydraulic power* and *constant voltage electric power*. An on-board computer uses a pressure sensor and a speed sensor to regulate the pressure and voltage by modulating a hydraulic solenoid valve and an engine throttle. The speed regulation also results in a system noise with predictable frequency band which allows for optimal muffler design. A novel characteristic of this power source is its cooling system in which hydraulic fluid is used to cool the engine cylinders. Several hydraulic-electric power units were built and successfully demonstrated on the Berkeley Lower Extremity Exoskeleton (BLEEX) shown on bleex.me.berkeley.edu/bleex.htm. A prototype power unit weighs 27 Kg, outputs 2.3 kW (3.0 hp) hydraulic power at 6.9 MPa (1000 psi), and 220 W of electric power at 15 VDC.**

Index Terms - mobile power sources, hydraulic power, power generation, field and service robotics, BLEEX

I. INTRODUCTION

Currently most human scale and field robotic systems are powered by tethers or heavy battery systems. In order for a robotic device to obtain energetic autonomy free from tethers and heavy batteries, a compact, portable power unit providing both mechanical power for actuation and electrical power for computation and control is essential.

Batteries are a common power source for mobile robots. The NiMH battery pack in ASIMO, Honda's humanoid walking robot [1], is one such example. However, batteries have a low specific energy (energy per mass): 0.5 MJ/kg for a high performance lithium ion battery [2]. Due to this low specific energy, batteries become large and heavy unless the operation time is short or the robotic system requires little power.

A fuel with a higher specific energy than batteries is desirable in a mobile robotic system. Previous work at the University of California, Berkeley focused on the use of a monopropellant-powered free piston hydraulic pump [2], [3]. This system generates hydraulic power through decomposition of 90%-concentrated hydrogen peroxide. Monopropellants are more energetic than batteries but their specific energy (1.2 MJ/kg for 90%-concentrated hydrogen peroxide) is significantly lower than that of a fuel such as gasoline (44 MJ/kg). Simplicity is a key advantage of monopropellants. The system requires no premixing, air compression, ignition, or cooling system. All one needs is to control the amount of monopropellant fuel through a solenoid valve via a computer to create a proper pressure differential in the two reactors. However the relatively low specific energy, the substantial required safety features, and the fuel cost prevented us from further pursuing monopropellant–based power units for robotic applications. See [4], [5] for another novel utilization of monopropellant in which fuel is directly converted to mechanical power.

Internal combustion (IC) engines utilize the high specific energy of gasoline. The power unit described here utilizes a two-stroke opposed twin cylinder IC engine to produce a compact, lightweight power source. This is primarily motivated by the fact that IC engines have been the primary source of power for automobiles, earthmoving machinery, motorcycles, and other wheeled vehicles. We envision mobile field robots as another class of these field vehicles that operate outdoors for periods of hours. In fact several field and service robotic systems have already experimented with IC engines as their prime mover [6] - [8].

IC engines, unfortunately, are loud. However it is our belief that current low volume market and small demand for small IC engines have prevented the development of the technologies that lead to efficient and quiet small engines for field robotic systems. Large volume field and mobile robotic systems will lead to development of quiet and efficient IC-engine-based power units. In fact, both Honda and Yamaha have already developed small, efficient, and quiet IC-engine-based portable electric power units for non-robotic outdoor applications with an optimized structure and muffler that produce a measured 75 db noise at 5 ft.

This paper describes the basic design challenges of a generic hydraulic-electric power unit (HEPU) for robotic applications. Although the design specifications for this power unit were derived from the operational requirements of BLEEX [9]-[11], the design rules apply to other field robotic systems. The architecture, hydraulic and electric power generation, cooling system and control are described in detail. Experimental data are presented to show the system performance.

This work is partially funded by DARPA grant DAAD19-01-1-0509.

II. HEPU SPECIFICATIONS

The design requirements for a mobile fieldable robotic system are functions of the robot size, its maneuvering speed, and its payload capability. The design of the hybrid power unit described here was motivated by the requirements of the BLEEX project [9] - [11]. After designing several power units, we have come to realize that mobile robotic systems with similar weight and size to BLEEX will require power sources with the same characteristics which differ only nominally. The main feature of BLEEX and many other field robotic systems that effects the design of their power units is the load carrying capability in the field. While many walking systems [12], [13] are designed to carry only their own weight, BLEEX was designed to carry external loads.

While high pressure hydraulics often leads to less power loss, we chose 6.9 MPa (1000 psi) as the system pressure. This leads to more reasonable hydraulic components for mobile systems that need to work in the field and perhaps in proximity of humans. We recommend higher working pressure (e.g. 20.7 MPa or 3000 psi) if safe and appropriate hydraulic delivery components can be incorporated in the system. The hydraulic flow requirements are usually calculated using the speed characteristics of the robot. High speed movements lead to large hydraulic flow requirements. In the case of the BLEEX project, the walking speed from CGA (clinical gait analysis) data [9] resulted in 20 LPM (5.2 GPM) of hydraulic flow. Our experience in building various exoskeleton systems suggest that one requires approximately 220 W of electric power for on-board robot computers and sensors in addition to the power unit sensors and controller. The mass target of the HEPU is 23 kg (50 lbs) to allow for a significant payload capacity. Table 1 summarizes the power unit specifications.

TABLE 1
HYDRAULIC ELECTRIC POWER UNIT (HEPU) SPECIFICATIONS FOR BLEEX

Hydraulic Fluid Power	2.3 kW (3.0 hp)
Electrical Power	220 W
Hydraulic Flow	20 LPM (5.2 GPM)
Working Pressure	6.9 MPa (1000 psi)
Mass Target	Less than 23 kg (50 lbs)
Maximum Noise Level	78 dBA at 1.5m (5ft)

III. OVERALL HEPU ARCHITECTURE

The HEPU is designed to provide electric and hydraulic power. It uses a compact two-stroke opposed twin cylinder IC engine capable of all-angle operation. Fig. 1 and Fig. 2 show how the engine (1) drives a single shaft (2) to power an alternator (3) for electric power generation, a cooling fan (4) for air circulation, and a gear pump (5) for hydraulic power generation. This single shaft design elegantly avoids noisy and heavy belt drive mechanisms common in systems comprising many rotating shafts. A hydraulic solenoid valve (7) regulates the hydraulic fluid pressure by directing the hydraulic flow from the gear pump to either an accumulator (10) or to the hydraulic reservoir (13). The accumulator consists of an aluminum cylinder in which a free piston separates the hydraulic fluid from the pressurized nitrogen gas. A carbon fiber tank (11) is attached to the gas side of the accumulator as reservoir for the nitrogen gas. In general the larger the volume of this gas reservoir is, the smaller the pressure fluctuation will be in the presence of hydraulic flow fluctuations. A pressure transducer (9) measures the pressure of the hydraulic fluid for the controller. A manifold (6) is designed to house both the solenoid valve (7) and filter (8). A novel liquid cooling scheme utilizes the returning hydraulic fluid itself to cool the engine. The hydraulic fluid from the robot actuators is divided into two paths. Approximately 38% of the hydraulic fluid is diverted to cool the engine cylinders. A heat exchanger (12) removes the heat from this hydraulic fluid before it reaches the hydraulic reservoir (13) and is mixed with the remaining 62% of the fluid.

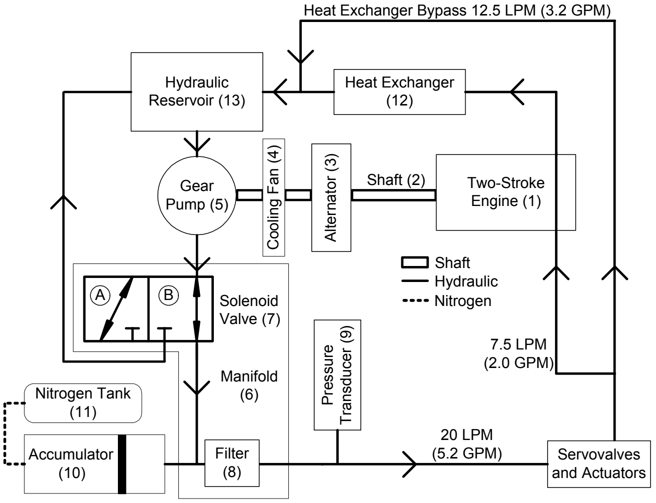

Fig. 1 HEPU schematic layout. Components labeled with numbers in parentheses also correspond to Fig. 2.

IV. MECHANICAL POWER PRODUCTION

The two-stroke opposed twin cylinder IC engine (model 80 B2 RV, manufactured by ZDZ Model Motor) capable of producing 6 kW (8.1 hp) of shaft power at 8200 rpm is used as the prime mover of this power unit. This engine has an 80 cm^3 displacement and weighs only 2 kg (4.4 lbs). Since the gear pump was limited to turn at maximum speed of 6300 rpm and since we intended not to utilize any transmission speed reducer in this power unit, we were forced to drive the engine at speeds lower than the maximum-power speed of the engine. The engine can produce approximately 3.06 kW (4.0 hp) at 6300 rpm which is greater than the required power (2.5 kW or 3.4 hp). In general, using a larger engine at lower speeds results in less noise than using a smaller engine at higher speeds. The engine is controlled with a servo motor mounted to its throttle.

The engine directly drives an alternator, a cooling fan and a gear pump. The pump (model WP03-B1B-032L-20MA12, manufactured by Haldex) has a 3.2 cm^3 displacement volume per revolution and therefore in theory it can transfer 20.2 LPM (5.3 GPM) of flow at its maximum speed of 6300 rpm.

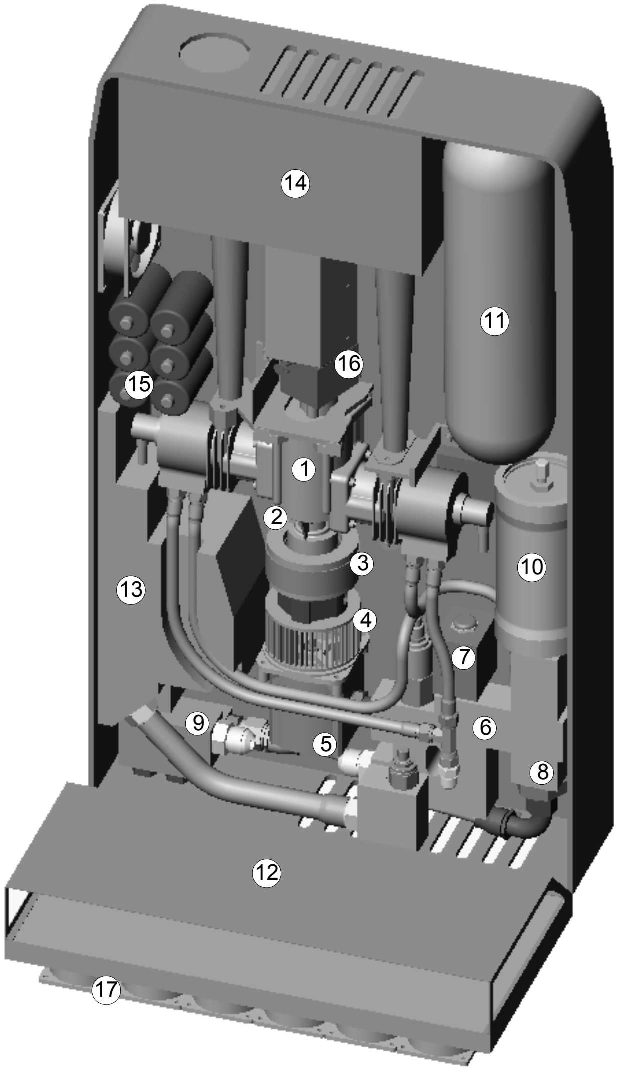

Fig. 2 HEPU physical layout. Engine (1); shaft (2, not visible); alternator (3); cooling fan (4); gear pump (5); manifold (6); solenoid valve (7); filter (8, not visible); pressure transducer (9, not visible); accumulator (10); nitrogen tank (11); heat exchanger (12); hydraulic reservoir (13); muffler (14); batteries (15); carburetor and throttle (16); heat exchanger fans (17). Internal baffling around engine is not shown for clarity.

V. CONTROL ARCHITECTURE

A unique control scheme was needed to maintain constant operating pressure with a fixed displacement pump running at a constant speed. An accumulator at the outlet of the pump supplies the fluid to the actuators and functions like a capacitor to compensate for transient peak flows. The hydraulic pressure is read by the pressure sensor. The computer controls the solenoid valve to maintain the pressure. When the pressure reaches the desired value (6.9 MPa in this case), the computer diverts the hydraulic flow to the reservoir by moving the valve to position A as shown in Fig. 1. To prevent pressure drop in the accumulator when the hydraulic fluid in the accumulator is consumed by the servovalves and the actuators, the computer diverts the flow to the accumulator by moving the valve to position B. The modulation of this valve based on the measured pressure allows the system to output hydraulic power at near constant pressure. The operating pressure in the accumulator is maintained in a band of 6.9 +/- 0.2 MPa (1000 +/- 30 psi).

When the solenoid valve diverts the hydraulic fluid to the reservoir, the engine speed increases rapidly. The opposite is also true: when the valve diverts the hydraulic fluid to the accumulator, the engine speed decreases rapidly and the engine might even stall. The variation of engine speed causes exhaust sound with varying frequencies that is undesirable for optimal noise reduction. Furthermore, the engine speed variation leads to a large voltage variation. Additionally the high engine speeds might damage the pump. For the above reasons, it is desirable to control the engine speed to a constant value. It was decided to maintain the speed at 6300 rpm (maximum allowable pump speed). In summary, an on-board computer uses a pressure sensor and a Hall effect sensor to regulate the pressure (at 1000 psi) and engine speed (at 6300 rpm) by modulating a hydraulic solenoid valve and an engine throttle.

VI. COOLING

Since the engine was designed for high performance model aircrafts, it requires a large amount of air for cooling its cylinders (air is generously available when the engine is installed on aircraft models.) For the application of field robotics, it is necessary to package the engine tightly in a sound-deadening shield; therefore liquid cooling was required. A novel liquid cooling scheme was devised that uses the hydraulic fluid itself to cool the engine. The engine cylinder heads were modified to allow hydraulic fluid to pass through them and absorb heat (Fig. 3). This makes the addition of a water-based cooling system unnecessary and results in a simplified system with fewer components. Using the hydraulic fluid as the cooling medium increases the load on the heat exchanger since the heat from the engine must be removed to prevent the hydraulic fluid from exceeding the operating temperature of any hydraulic components. The maximum temperature allowable was determined by the pump which had the lowest temperature tolerance of any component in the system (the gear pump required hydraulic fluid temperature cooler than 65° C or 149° F).

The fluid returning from the actuators is split into two separate paths, as shown in Fig. 4. Approximately 62% of the hydraulic fluid returns directly to the reservoir. The remaining 38% passes first through the cylinder heads where excess heat is extracted from the engine, then through a heat exchanger where the heat in the fluid is dissipated, and finally returns to the reservoir. As shown in Fig. 4, the heat exchanger must remove the heat generated from the dissipative effect of the servovalves on the actuators in addition to the heat generated in the engine cylinder heads. Increasing fluid volume in the reservoir increases convective heat transfer (cooling) to ambient air and allows longer operation times. This is a typical solution in industrial hydraulics, but is not feasible in this application where a large reservoir is undesirable. Therefore, careful sizing of the heat exchanger was critical to ensure adequate cooling at a minimum weight.

A thermal model was created (using measured data from the test stand whenever possible) to estimate the behavior of the hydraulic system and evaluate the hydraulic fluid temperature at the most sensitive component, the pump. Data was taken from an experimental run with the engine producing 3.06 kW of shaft power. A duty cycle of 50% was used to simulate our operating conditions (i.e., 1.53 kW continuous shaft power). The reservoir was modeled as a perfect mixer with zero heat transfer to ambient. The pump exhibited a minimum of 80% efficiency (shaft power to fluid power); hence 20% of the engine shaft power (3.06 kW*0.50*0.20 = 0.306 kW or 0.41 hp) is converted to heat into the hydraulic fluid. The heat transfer to ambient air in the hydraulic lines was estimated at -0.373 kW (-0.50 hp). The actuators and servovalves were assumed to convert all the hydraulic power flowing through them to heat into the hydraulic fluid (3.06 kW*0.50*0.80 = 1.22 kW or 1.64 hp). The sum of the heat transfer rates from the reservoir, pump, lines, and valves is $\dot{Q}_{Other} = (1.22 + 0.306 - 0.373) = 1.15$ kW (1.54 hp). The heat transfer rate from the engine cylinders, $\dot{Q}_{Engine}$, was measured at 2.85 kW (3.82 hp). The performance of the heat exchanger is characterized by a thermal parameter K_{th} which is the heat transfer rate at a given flow rate of fluid divided by the initial temperature difference between the hot fluid entering the heat exchanger and the environment at $T_{ambient}$.

$$\dot{Q}_{Exchanger} = -K_{th}(T_2 - T_{ambient}) \quad (1)$$

The temperature T_4 in Fig. 4 is equal to the pump inlet temperature since there is no heat transfer in the reservoir. At steady state the heat transfer from each component can be expressed by the following equations.

$$\dot{Q}_{Other} = \dot{m}_{total} c_P (T_1 - T_4) \quad (2)$$

$$\dot{Q}_{Engine} = \dot{m}_{cool} c_P (T_2 - T_1) \quad (3)$$

$$\dot{Q}_{Exchanger} = \dot{m}_{cool} c_P (T_3 - T_2) \quad (4)$$

where $\dot{m}_{total}$ is the total hydraulic mass flow rate, $\dot{m}_{cool}$ is the cooling flow rate, and c_P is the specific heat of the fluid. Since at steady state:

$$\dot{Q}_{Exchanger} + \dot{Q}_{Engine} + \dot{Q}_{Others} = 0 \quad (5)$$

equations (1) – (5) can be solved explicitly for the steady state pump inlet temperature, T_4.

$$T_4 = T_{ambient} - \frac{\dot{Q}_{Exchanger}}{K_{th}} - \frac{\dot{Q}_{Engine}}{\dot{m}_{cool} c_P} - \frac{\dot{Q}_{Other}}{\dot{m}_{total} c_P} \quad (6)$$

Various heat exchanger specifications were inserted in (6) to estimate the steady state hydraulic fluid temperature and evaluate the performance of a given heat exchanger. At steady state the selected heat exchanger removes 4.00 kW and the calculated pump inlet temperature is 61°C (141°F), under the maximum allowable pump temperature, 65°C.

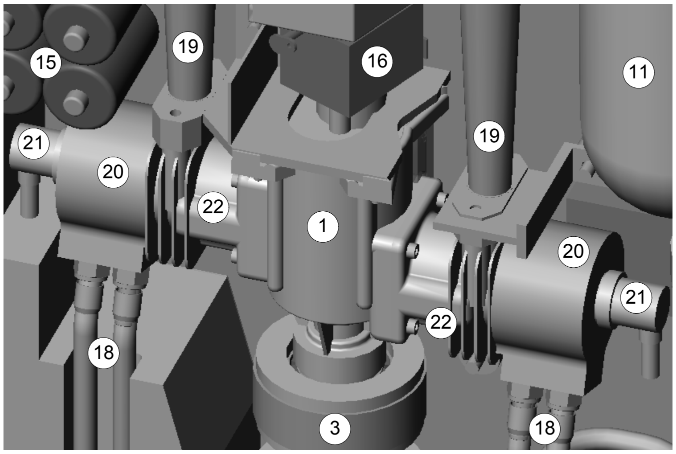

Fig. 3 Detail of the engine depicting the cooling jackets on the cylinders. Engine (1); alternator (3); nitrogen tank (11); batteries (15); carburetor and throttle (16); hydraulic lines (18); exhaust pipe (19); cooling jacket (20); spark plug (21); cylinder head (22).

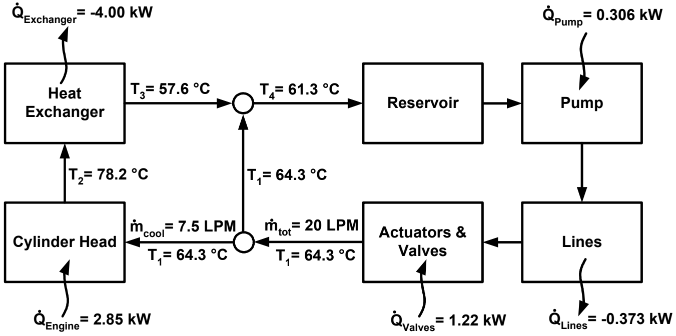

Fig. 4 Cooling system schematic of the HEPU.

VII. ELECTRICAL POWER GENERATION

The HEPU generates electrical power for the sensors, cooling fans, and the control computer. The electrical power generation and regulation design is depicted in Fig. 5. The total electrical system power budget is 220 W, with 100 W for cooling fans and 65 W for the control computer and sensors. The remaining 55 W are expected to be consumed in losses and other peripheral components. A three phase, 12-pole frameless, brushless DC motor (model RBE-1812, manufactured by Kollmorgen) is used as an electric power generator (3 in Fig. 2). The three phases were converted to single-phase, 240 VDC by a bridge rectifier (the back EMF constant of the motor is 26.9 V/krpm so that at the operational speed of 6300 rpm the rectified voltage is 240 VDC). Two DC-DC converters are used to create two 15 VDC bus voltages to be used for two sets of components. One 15 VDC line is used to power the electrically noisy components such as solenoid valves, cooling fans, and the ignition for the engine. The second 15 VDC line is used to charge a set of batteries, power the control computer, HEPU controller, and the throttle servo. The external power (shown in Fig. 5) is used to power the system when the engine is off. The battery shown in Fig. 5 powers the control computer, HEPU controller, throttle servo, and sensors for a short time in case the engine shuts down. This gives the operator ample time to connect external power to the system. The HEPU controller measures and regulates two important variables: engine speed and hydraulic pressure. While regulation of the hydraulic pressure is important for the robot control, regulation of the engine speed manifests to a constant output voltage and constant engine noise frequency. A constant engine noise frequency is important in the design of an optimal muffler. The engine speed is measured by counting the pulses from a Hall effect sensor on the alternator. The HEPU controller outputs are the solenoid valve and servo. While the solenoid valve regulates the pressure, the servo ensures constant speed (6300 rpm). The HEPU also measures engine and hydraulic fluid temperature and controls the heat exchanger fans (17 in Fig. 2).

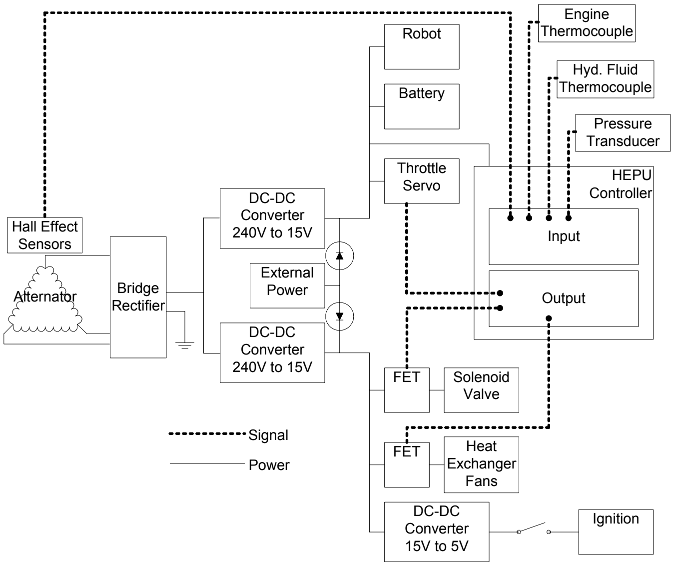

Fig. 5 Electrical schematic.

VIII. HEPU LAYOUT

Any robotic power source must be packaged so that it leaves a maximum of useable space for the robot and its payload. It is simplest to package the power source by layering components around the engine, but this tends to create a roughly cubic shape that must be integrated into the robotic system. The HEPU design focused on creating a power source that was as thin as possible in one dimension to make integration simple. Such a design may be attached to a robotic system on any available side or in any available space without impeding its functionality. Since the heat exchanger for cooling must exhaust freely to the atmosphere, it is left as a separate attachment to be placed as convenient. In Fig. 2 it is shown on the bottom of the power source as a shelf so that payload could be placed above the heat exchanger.

Reducing the thickness of the power source drove many of the design decisions. The two-stroke engine has a carburetor mounted parallel to the crankshaft and can be configured so that the exhaust ports are also parallel to the crankshaft which allows it to fit in an extremely thin package. Similarly the fuel was stored in the hollow back panel of the device rather than a separate fuel tank. Even the muffler was custom designed to fit exactly into the power source. The result was a 10 cm (4 inch) thick power source design that could be integrated into many robotic systems.

IX. NOISE ABATEMENT

At the outset of the HEPU design, a 78 dBA noise specification was set (measured at a distance of 1.5 m or 5 ft from the HEPU at full power). 75 dBA is approximately the noise level of a commercially available 2kW generator, which uses a quieter four-stroke engine. Reaching such a low level of noise with a two-stroke engine, notorious for high noise levels, was probably unrealistic. Two strategies were used to reduce the noise to tolerable levels. First, the engine was set to run at a constant rpm so that the muffler could be optimized to constant frequencies. Second, direct paths to the engine were eliminated through the use of liquid cooling and baffles around the engine. Two nested sheet metal containment shells were constructed using welded 1.6 mm (0.062 in) thick aluminum and placed over the engine. The containment shells were sprayed on both sides with 2-3mm of viscoelastic damper material. The inside of the containment shells were further lined with 10 mm thick open cell polyimide foam. An intake muffler was constructed using an aluminum box filled with polyester reticulated foam. The muffler was used with its output pipe exhausting outside of both containment shells. The best noise level obtained when measured outdoors was 87 dBA, significantly above the desired noise level of 78 dBA. The muffler is responsible for the greatest sound reduction; the sound shield was marginally effective.

X. PERFORMANCE EVALUATION

An instrumented test stand was built with all the components of the HEPU design except the electrical system and pressure regulation, which are similar to those installed on older BLEEX power units. Fig. 6 shows an experiment where the system pressure is changed from 1.4 MPa to 7.5 MPa while the controller maintains a constant speed. Testing also confirmed that the HEPU approximately met the flow requirements with 19.4 LPM (5.1 GPM) of flow at a pressure of 7.4 MPa (1073 psi) resulting in 2.4 kW (3.2 hp) of hydraulic power, as shown in the steady state run in Fig. 7.

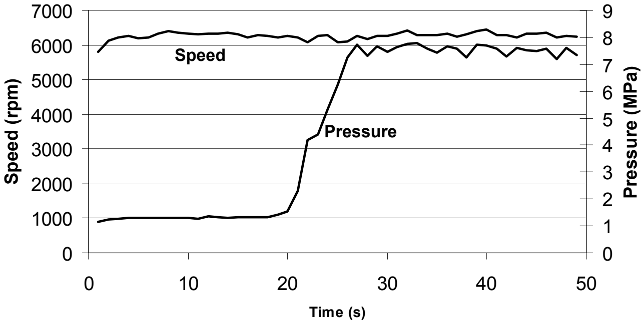

Fig. 6 Automatic throttle control on the test stand.

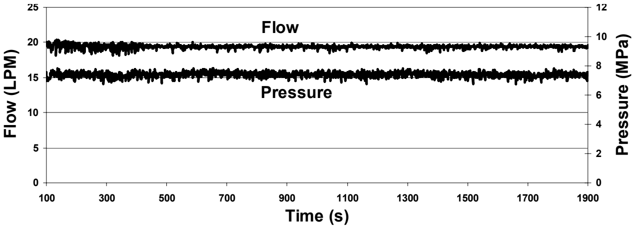

Fig. 7 The power source is able to produce 19.4 LPM, at 7.4 MPa. No accumulator was installed on the test stand to compensate for transient effects.

XI. CONCLUSION

The HEPU as designed would meet the requirements of hydraulic and electrical power, but exceed both the target mass and noise output. Fig. 8 shows the mass budget for the power unit. It can be seen that the power unit reached an approximate dry mass of 27 kg or a wet mass of near 30 kg for one hour of operation. This is significantly over the target mass of 23 kg. Examination of Fig. 8 shows that the engine itself contributes only 2 kg or 7% of the total system mass. Therefore, to design a lighter system, one needs to reduce the mass of other components. Reducing the mass of the power unit components if not impossible is a difficult task that needs technologies that are not currently available. Also note that the amount of system mass dedicated to noise abatement is very large, approaching 11 kg or 35% of the total mass.

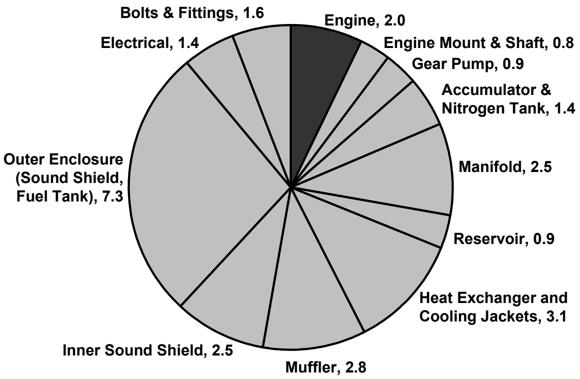

Fig. 8 Mass budget in kg (27 kg total).

The mass of the noise abatement system forced us to consider other methods of noise abatement and their impacts on the overall system mass. To compare the designed power unit with other designs, we introduce a *Performance Index* (PI):

$$PI = \frac{power(watts)}{mass(kg) \bullet noise(dBA)} \quad (7)$$

A design meeting the required specifications shown in Table 1 would score a PI = 1.57. Five different designs were compared using the PI of (7) in Table 2. Based on Table 2, the *power*, *mass*, and *noise* of any engine-based power source are fundamentally related to each other. Power comes at the cost of noise or mass, i.e., a more powerful system will be either nosier or heavier. Alternatively a lighter system will be either nosier or less powerful. We have seen this trade-off repeatedly in all power units we built for the BLEEX project. According to our experience and our analysis, the performance index PI for most designs fall into a narrow range of PI values shown in Table 2; it is unlikely that existing technology will lead to any system with a PI substantially larger than what is shown in Table 2.

TABLE 2
POWER SOURCE SOLUTIONS

	Existing system	Existing system, no noise reduction	2kW generator (Honda EU2000)	1kW generator (Honda EU1000)	Fuel cell (MES-DEA 3.0)
Dry mass (kg)	27	20	23	18	30
Noise (dBA)	87	97	77	77	72
Shaft power used (kW)	2.7	2.7	2	1.3	2.55
Performance Index	1.15	1.39	1.13	0.94	1.18

Notes: Mass based on detailed mass budgets. Shaft power for generators is based on 75% of the rated power of the engines. Shaft power for fuel cell assumes 85% efficient motor and motor amplifier.

REFERENCES

[1] Y. Sakagami, et al, “The Intelligent ASIMO: System overview and Integration,” Proc. of the 2002 IEEE/RSJ Intl. Conference on Intelligent Robots and Systems EPFL, Lausanne Switzerland, October 2002, pp. 2478-2483.

[2] J.W. Raade, T.G. McGee, and H. Kazerooni, “Design, Construction, and Experimental Evaluation of a Monopropellant Powered Free Piston Hydraulic Pump,” Proc. of ASME International Mechanical Engineering Congress and Exposition, Washington, D.C., 2003.

[3] T. G. McGee, J. W. Raade, and H. Kazerooni, “Monopropellant-Driven Free Piston Hydraulic Pump for Mobile Robotic Systems,” *ASME J. of Dynamic Sys., Meas., and Control*, vol. 126, no. 1, March 2004, pp. 75–81.

[4] E. J. Barth, M. A. Gogola, J. A. Wehrmeyer, and M. Goldfarb, “The Design and Modeling of Liquid-Propellant-Powered Actuator for Energetically Autonomous Robots,” Proc. ASME International Mechanical Engineering Congress & Exposition, New Orleans, LA, 2002.

[5] M. Gogola, E. J. Barth, and M. Goldfarb, “Monopropellant Powered Actuators for Use in Autonomous Human Scale Robotics,” Proc. IEEE International Conference on Robotics and Automation, Washington, D.C., 2002, pp. 2357-2362.

[6] P. Weiss, “Dances with Robots”, *Science News*, vol. 159, no. 25, June 2001, pp. 407-408.

[7] E. Colin, D. Polome, V. Piedfort, and Y. Baudoin, “AMRU 3: a teleoperated six-legged electro-hydraulic robot,” In *Mobile Robots IX*, William J.Wolfe, Wendell H. Chun, Editors, Proc. SPIE 2352, 1995, pp. 192-203.

[8] Timberjack, “The walking forest machine” The walking forest machine website, Retrieved 9-3-2004 from http://www.plustech.fi/Walking1.html

[9] A. Chu, H. Kazerooni, and A. Zoss “On the Biomimetic Design of the Berkeley Lower Extremity Exoskeleton (BLEEX),” Proc. of IEEE International Conference on Robotics and Automation, Barcelona, Spain, 2005.

[10] H. Kazerooni, L. Huang, J. L. Racine, and R. Steger “On the Control of Berkeley Lower Extremity Exoskeleton (BLEEX),” Proc. of IEEE International Conference on Robotics and Automation, Barcelona, Spain, 2005.

[11] A. Zoss and H. Kazerooni “On the Mechanical Design of the Berkeley Lower Extremity Exoskeleton (BLEEX),” Proc. of IEEE Intelligent Robots and Systems, Edmonton, Canada, 2005.

[12] H. Kawamoto, and Y. Sankai, "Power Assist System HAL-3 for Gait Disorder Person." Lecture Notes In Computer Science (LNCS), Vol. 2398, Proceedings of the Eighth International Conference on Computers Helping People with Special Needs, Berlin, Germany, 2002, pp. 196-203.

[13] M. Vukobratovic, B. Borovac, D. Surdilovic, and D. Stokic, “Humanoid Robots”, Mechanical Systems Design Handbook. CRC Press, 2002.