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DEVELOPMENT OF HYDRAULIC-ELECTRIC POWER UNITS FOR MOBILE ROBOTS

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ABSTRACT

Energetic autonomy of a hydraulic-based mobile robot requires a power source capable of both hydraulic and electrical power generation. The hydraulic power is used for locomotion and the electric power is used for the control computer, sensors and other peripherals. In addition, the power source must be lightweight and quiet. This study presents several designs of internal combustion engine-based power units. Each power unit is evaluated with a Ragone plot which shows its performance over a wide range of operation times. The best-performing design of the hydraulic-electric power units (HEPU), based upon the Ragone plot analysis, is described in detail. This HEPU produces constant pressure hydraulic power and constant voltage electric power. The pressure and voltage are controlled on board the power unit by a computer. A novel characteristic of this power unit is its cooling system in which hydraulic fluid is used to cool the engine cylinders. The prototype power unit weighs 27 kg and produces 2.3 kW (3.0 hp) hydraulic power at 6.9 MPa (1000 psi) and 220 W of electric power at 15 VDC.

INTRODUCTION

Most human scale and field robotic systems are currently 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. The NiMH battery pack in ASIMO, Honda's humanoid walking robot, is one example of a battery-based power unit [1]. However, batteries have a low specific energy (energy per unit mass): 150 W-hr/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. Internal combustion (IC) engines utilize the high specific energy of gasoline: 12000 W-hr/kg. The power units described here utilize IC engines to produce compact, lightweight power sources. 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 [3]-[4].

This paper describes the basic design challenges of a generic hydraulic-electric power unit (HEPU) for robotic applications. First, an analysis of the HEPU systems based on Ragone plots is presented. Then the specifications of several versions of the HEPU are described. Finally, the final architecture of the HEPU, including its hydraulic and electric power generation, cooling system, and control, is described in detail.

RAGONE PLOT ANALYSIS

Ragone plots are useful for evaluating the performance of a power unit for a wide range of operation times [5]. They plot the power unit's specific power (power divided by total mass) versus the specific energy (energy divided by total mass). The specific energy $\hat{E}$ can be expressed by

$$\hat{E} = \frac{E_{tot}}{m_{tot}} = \frac{P_{tot}\tau}{m_{fuel} + m_{tank} + m_{eng}} \tag{1}$$

where E_{tot} is the total energy required for the operation time τ of the system, m_{tot} is the total power unit mass including the mass of the fuel m_{fuel}, fuel tank m_{tank}, and engine m_{eng}, and P_{tot} is the total output power (hydraulic power plus electrical power). The mass of the fuel is

$$m_{fuel} = \frac{E_{tot}}{\eta \hat{h}} \tag{2}$$

where $\hat{h}$ is the specific energy of the fuel and η is the overall efficiency. The overall efficiency is defined as the total output power divided by the fuel power (measured fuel flow rate $\dot{m}_{fuel}$ times specific energy $\hat{h}$ of the fuel) flowing into the engine.

$$\eta = \frac{P_{tot}}{\dot{m}_{fuel} \hat{h}} \tag{3}$$

The mass of the fuel tank is proportional to the mass of the fuel, and can be expressed by

$$m_{tank} = \frac{m_{fuel}}{\beta} \tag{4}$$

where β is a constant defined as the ratio of fuel mass to the mass of the tank required to hold the fuel. Using Equations (2) and (4) in Equation (1) and simplifying produces

$$\hat{E} = \left[\frac{1}{\eta \hat{h}} \left(1 + \frac{1}{\beta} \right) + \frac{m_{eng}}{P_{tot} \tau} \right]^{-1} . \tag{5}$$

The specific power $\hat{P}$ can be similarly expressed as

$$\hat{P} = \frac{P_{tot}}{m_{tot}} = \frac{\hat{E}}{\tau} . \tag{6}$$

Several valuable trends can be learned by examining a Ragone plot. As the operation time τ becomes very long, the specific power $\hat{P}$ approaches zero while the specific energy $\hat{E}$ tends toward a finite value. This can be shown by examining Equations (5) and (6) as the operation time approaches infinity.

$$\begin{aligned} \lim_{\tau \to \infty} \hat{E} &= \eta \hat{h} \left(\frac{\beta}{\beta + 1} \right) \\ \lim_{\tau \to \infty} \hat{P} &= 0 \end{aligned} \tag{7}$$

Alternatively, as the operation time becomes very short, the specific energy approaches zero while the specific power approaches a finite value. As the operation time approaches zero, Equations (5) and (6) become:

$$\begin{aligned} \lim_{\tau \to 0} \hat{E} &= 0 \\ \lim_{\tau \to 0} \hat{P} &= \frac{P_{tot}}{m_{eng}} \end{aligned} \tag{8}$$

If one is concerned with very long operation times for a mobile robotic power unit, then Equation 7 shows that the most critical parameters of the power unit are the *overall efficiency*, the *specific energy of the fuel*, and the *fuel storage ratio*. For a power unit designed for very short operation times, Equation 8 shows that the most critical parameters are the *total power* and the *engine mass* (the fuel and fuel tank mass are negligible).

Mobile robotics require lightweight power units in order to operate effectively in the field. Therefore, it is imperative to find the lightest power unit for a given operation time. Using a Ragone plot to evaluate the power units described in this work enabled us to determine the lightest choice for a given application. Figure 1 shows a Ragone plot of each HEPU system developed at the University of California, Berkeley. All the HEPU systems use gasoline with a fuel storage ratio β = 4 (based on a sturdy plastic tank holding the gasoline). The diagonal lines correspond to constant operation times on a logarithmic scale. Based on the information illustrated in Figure 1, for operation times less than approximately ten hours the lightest power unit is the ZDZ80-based HEPU due to its high specific power. For very long operation times greater than ten hours, the lightest system is the GX31-based HEPU due to its high overall efficiency. In general, two-stroke engines have more power per unit mass (specific power) than four-stroke engines, making the two-stroke HEPU systems lighter for short operation times. Four-stroke engines, on the other hand, have a higher efficiency than two-strokes, making the four-stroke HEPU systems lighter for long operation times.

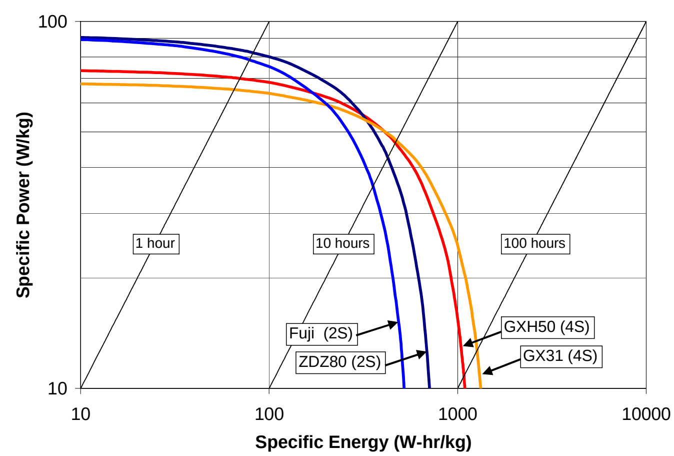

Figure 1: Ragone plot of HEPU systems, labeled by engine name. The two-stroke power units are labeled "2S" and the four-strokes are labeled "4S."

SEQUENCE OF HEPU DESIGNS

GENERAL ARCHITECTURE

All of the HEPU designs presented in this work have the same general architecture as shown in Figure 2. The engine provides the shaft power which turns a hydraulic pump to produce hydraulic flow for the actuators of the robotic system. The engine also spins an alternator which provides electrical power for the sensors, control computers, and ancillary equipment such as cooling fans or pumps. The power units described herein can be utilized by any hydraulic robotic system.

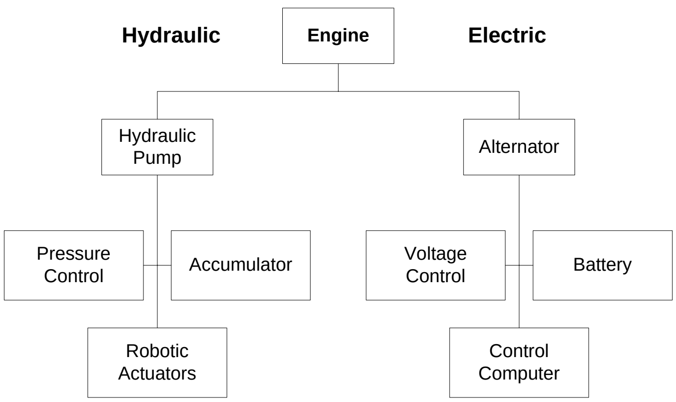

Figure 2: HEPU system architecture.

HONDA GX31-BASED HEPU

The Honda four-stroke engine GX31 serves as the prime mover in the first generation HEPU. A hydraulic schematic for the GX31-based HEPU is shown in Figure 3.

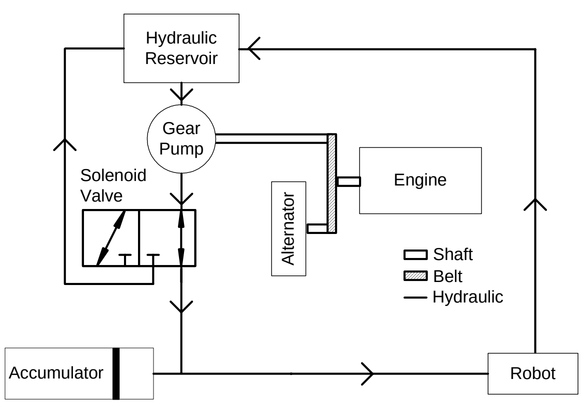

Figure 3: Hydraulic schematic of GX31 HEPU.

The engine spins a gear pump and alternator via a belt drive. A solenoid valve maintains the hydraulic pressure by rerouting the flow from the pump back to the reservoir when the pressure in the accumulator reaches the desired value. An independent speed governor on the engine maintains the electrical voltage by maintaining a constant engine speed. A photograph of the system is shown in Figure 4. The system specifications are listed in Table 1. The GX31 HEPU proved to be a lightweight power unit suitable for a robotic system with low hydraulic flow requirements.

Figure 4: Honda GX31 HEPU.

Description	First generation HEPU
Engine	Honda GX31 4-stroke, air cooled, centrifugal clutch
Hydraulic power	750 W (5.3 LPM @ 6.2 MPa) 1.0 HP (1.4 GPM @ 900 psi)
Electrical power	120 W (Aveox three phase brushless motor/alternator)
Transmission	Double belt drive with hydraulic pump and electrical alternator
Hydraulic pump	Haldex W600 gear pump
Pressure and voltage control	Solenoid hydraulic bypass valve, bang-bang throttle control
Overall efficiency (η)	16%
Mass without fuel or tank (m_{eng})	13 kg (28 lbs)

Table 1: GX31 HEPU specifications.

HONDA GXH50-BASED HEPU

The second generation HEPU has the same hydraulic and electrical architecture as the first generation HEPU (Figure 3), but utilizes the Honda four-stroke engine GXH50 for a significant power increase over the GX31. This power unit was used extensively for field testing of the Berkeley lower extremity exoskeleton (BLEEX) [6]-[8]. Figure 5 shows a photograph of the system. The system specifications are listed in Table 2.

Figure 5: Honda GXH50 HEPU.

Description	Second generation HEPU
Engine	Honda GXH50 4-stroke, air cooled, centrifugal clutch
Hydraulic power	1.0 kW (9.1 LPM @ 6.9 MPa) 1.4 HP (2.4 GPM @ 1000 psi)
Electrical power	100 W (Faulhaber three phase brushless motor/alternator)
Transmission	Double belt drive with hydraulic pump and electrical alternator
Hydraulic pump	Haldex W600 gear pump
Pressure and voltage control	Solenoid hydraulic bypass valve, stock governor throttle control
Overall efficiency (η)	13%
Mass without fuel or tank (m_{eng})	15 kg (34 lbs)

Table 2: GXH50 HEPU specifications.

FUJI BT50SA-BASED HEPU

A two-stroke engine (the Fuji BT50SA) was chosen for a new HEPU design due to its light weight and high power output [9]. Figure 6 shows a hydraulic schematic of the Fuji-based HEPU. In contrast to the previous HEPU systems, an electrically-actuated clutch maintains hydraulic pressure by disconnecting the engine from the pump when the desired pressure is reached in the accumulator. A CAD image of the system is shown in Figure 7. The system specifications are listed in Table 3. The Fuji-based HEPU was evaluated on a test stand but not fully constructed due to its high noise level.

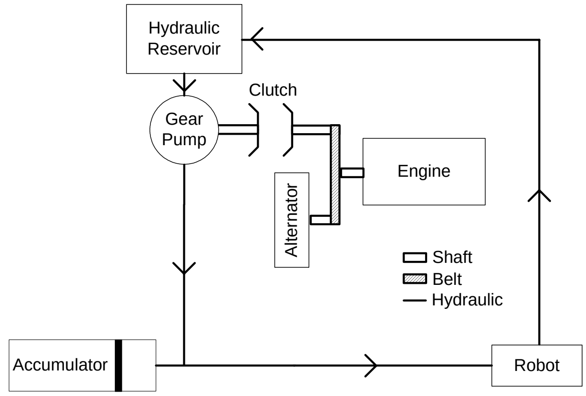

Figure 6: Hydraulic schematic of Fuji BT50SA HEPU.

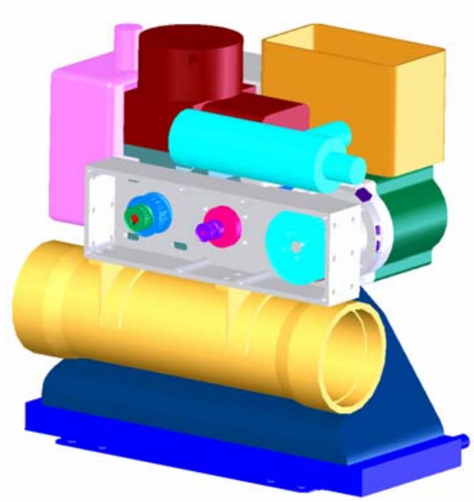

Figure 7: CAD model of Fuji BT50SA HEPU.

Description	Third generation HEPU
Engine	Fuji BT50SA 2-stroke, liquid cooled, solenoid activated clutch
Hydraulic power	1.1 kW (15 LPM @ 4.1 MPa) 1.5 HP (4.0 GPM @ 600 psi)
Electrical power	120 W (Aveox three phase brushless motor/alternator)
Transmission	Double belt drive with hydraulic pump and electrical alternator
Hydraulic pump	Haldex W600 gear pump
Pressure and voltage control	Bang-bang electric clutch bypass, computer-controlled engine speed
Overall efficiency (η)	6.0%
Mass without fuel or tank (m_{eng})	14 kg (30 lbs)

Table 3: Fuji BT50SA HEPU specifications.

ZDZ80-BASED HEPU

A HEPU system with integrated noise deadening measures was realized with a ZDZ80 two-stroke engine. Figure 8 shows a CAD image of the system. The system specifications are listed in Table 4. See the section on the ZDZ80 HEPU for a detailed description of the design of this power unit.

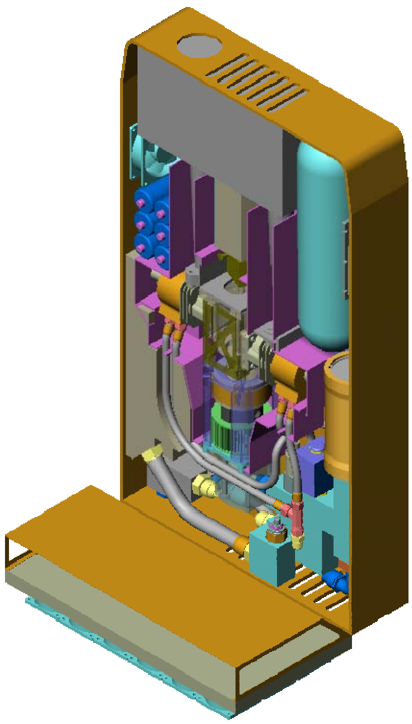

Figure 8: ZDZ80 HEPU.

Description	Fourth generation HEPU
Engine	ZDZ-80 2-stroke, liquid cooled, direct drive
Hydraulic power	2.3 kW (20 LPM @ 6.9 MPa) 3.0 HP (5.2 GPM @ 1000 psi)
Electrical power	220 W (Kollmorgen RBE series, three phase brushless motor/alternator)
Transmission	In-line direct drive of pump and alternator
Hydraulic pump	Haldex W300 gear pump
Pressure and voltage control	Solenoid hydraulic bypass valve, computer-controlled engine speed
Overall efficiency (η)	8.1%
Mass without fuel or tank (m_{eng})	27 kg (59 lbs)

Table 4: ZDZ80 HEPU specifications.

DETAILED DESIGN OF ZDZ80-BASED HEPU

The following sections summarize a more complete description of the ZDZ80-based HEPU design found in [10].

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 main feature of many field robotic systems that affects the design of their power units is the load carrying capability in the field.

While high pressure hydraulics often lead 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. 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 resulted in 20 LPM (5.2 GPM) of hydraulic flow [6]. Our experience in building various exoskeleton systems suggest that one requires approximately 220 W of electric power for on-board robot computers and sensors as well as the power unit sensors and controller.

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. Figure 9 and Figure 10 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.

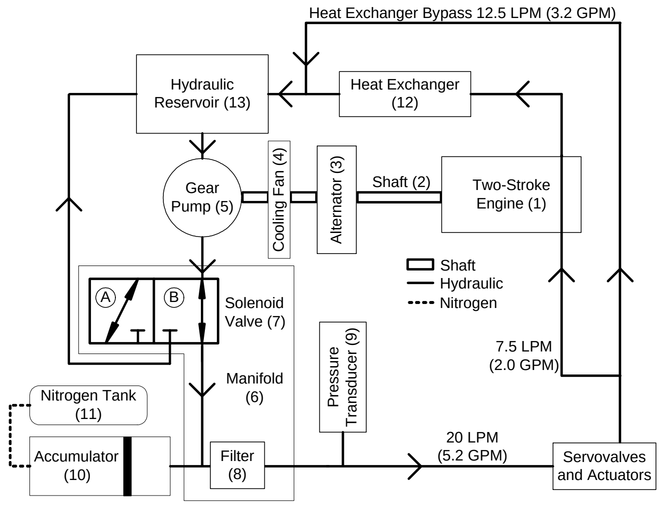

Figure 9: HEPU schematic layout. Components labeled with numbers in parentheses also correspond to Figure 10.

HYDRAULIC 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 did not intend 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) of shaft power at 6300 rpm which is adequate to produce the total output hydraulic and electrical power (2.5 kW or 3.4 hp). 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.

CONTROL

The HEPU controller measures and regulates two important variables: engine speed and hydraulic pressure. 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 in Figure 9. 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 back to the accumulator by moving the valve to position B. The modulation of this valve based on the measured pressure allows the system to produce 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).

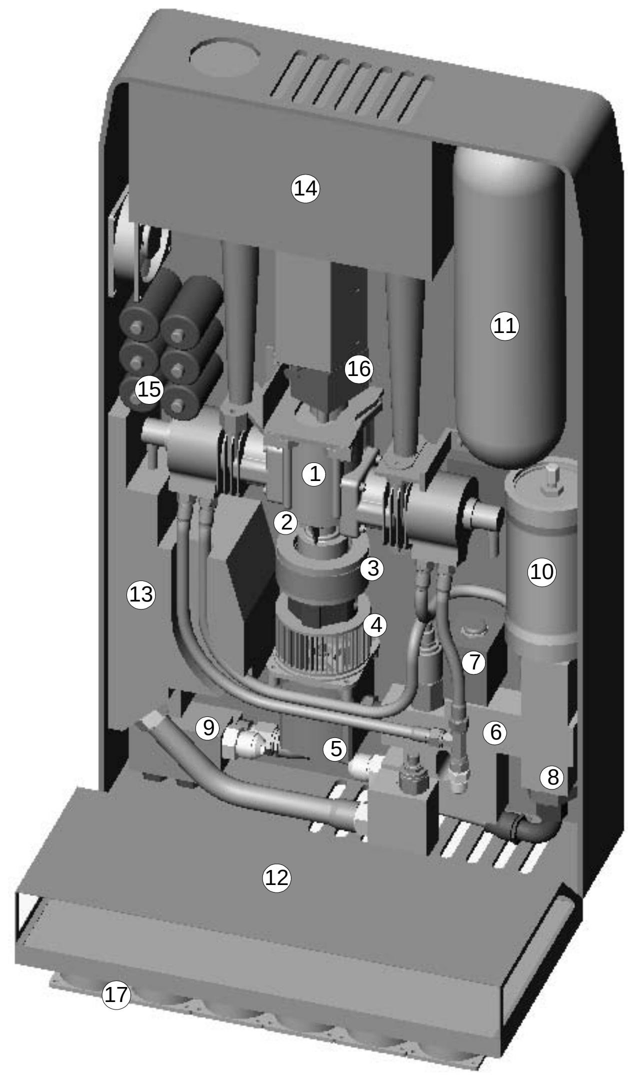

Figure 10: HEPU physical layout. Engine (1); shaft (2, not visible); alternator (3); cooling fan (4); gear pump (5); manifold (6); solenoid valve (7); filter (8, not visible); pressure transducer (9, not visible); accumulator (10); nitrogen tank (11); heat exchanger (12); hydraulic reservoir (13); muffler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

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 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). The engine speed is measured by counting the pulses from a Hall effect sensor on the alternator. An on-board computer modulates the engine throttle with a servo.

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. 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 Figure 11. 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 Figure 11, 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 a 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 [10]. At steady state the heat exchanger removes 4.00 kW of heat and the calculated pump inlet temperature is 61°C (141°F), under the maximum allowable pump temperature, 65°C.

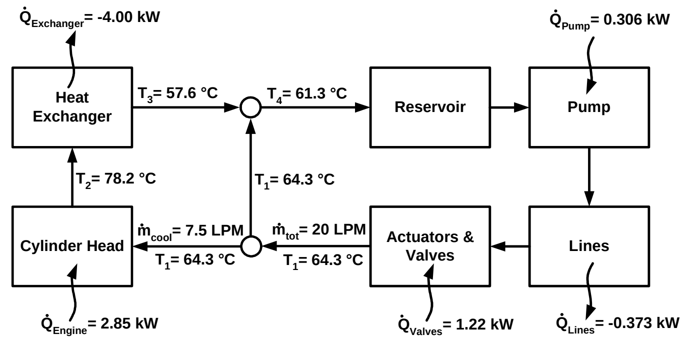

Figure 11: Cooling system schematic of the HEPU with calculated heat flow and temperature values.

ELECTRICAL POWER GENERATION

The HEPU generates electrical power for the sensors, cooling fans, and the control computer. 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 alternator (3 in Figure 10). 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. External power is used to power the system when the engine is off. A battery 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.

CONCLUSION

Gasoline-fueled hydraulic power units are capable of producing mobile robotic power. When the system mass is the most critical parameter, Ragone plots are very useful for determining the best design of a power unit that minimizes the system mass for a given operation time. The ZDZ80-based HEPU as designed produces constant-pressure hydraulic power (2.3 kW) and constant-voltage electrical power (220 W) for a mobile robotic system.

ACKNOWLEDGMENTS

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