A Power Autonomous Monopedal Robot

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ABSTRACT

We present the design and initial results of a power-autonomous planar monopedal robot. The robot is a gasoline powered, two degree of freedom robot that runs in a circle, constrained by a boom. The robot uses hydraulic Series Elastic Actuators, force-controllable actuators which provide high force fidelity, moderate bandwidth, and low impedance. The actuators are mounted in the body of the robot, with cable drives transmitting power to the hip and knee joints of the leg. A two-stroke, gasoline engine drives a constant displacement pump which pressurizes an accumulator. Absolute position and spring deflection of each of the Series Elastic Actuators are measured using linear encoders. The spring deflection is translated into force output and compared to desired force in a closed loop force-control algorithm implemented in software. The output signal of each force controller drives high performance servo valves which control flow to each of the pistons of the actuators.

In designing the robot, we used a simulation-based iterative design approach. Preliminary estimates of the robot's physical parameters were based on past experience and used to create a physically realistic simulation model of the robot. Next, a control algorithm was implemented in simulation to produce planar hopping. Using the joint power requirements and range of motions from simulation, we worked backward specifying pulley diameter, piston diameter and stroke, hydraulic pressure and flow, servo valve flow and bandwidth, gear pump flow, and engine power requirements. Components that meet or exceed these specifications were chosen and integrated into the robot design. Using CAD software, we calculated the physical parameters of the robot design, replaced the original estimates with the CAD estimates, and produced new joint power requirements. We iterated on this process, resulting in a design which was prototyped and tested.

The Monopod currently runs at approximately 1.2 m/s with the weight of all the power generating components, but powered from an off-board pump. On a test stand, the eventual on-board power system generates enough pressure and flow to meet the requirements of these runs and we are currently integrating the power system into the real robot. When operated from an off-board system without carrying the weight of the power generating components, the robot currently runs at approximately 2.25 m/s. Ongoing work is focused on integrating the power system into the robot, improving the control algorithm, and investigating methods for improving efficiency.

1. INTRODUCTION

Practical legged robots are challenging for a number of reasons, including dynamic balance requirements, design complexity, and power requirements. To investigate power-autonomous legged robots we have been developing a power-autonomous Monopedal robot that is powered from a two stroke engine, which drives a high-pressure hydraulic system. The Monopod is a planar robot, confined to the surface of a sphere by a 12 foot radius boom. It has two degrees of freedom: a hip and a knee. Hydraulic Series Elastic Actuators are located in the body and transmit power to the hip and knee through cables.

The Monopod is intended to be a test platform for a variety of technologies including:

- Hydraulic Series Elastic Actuators. Series Elastic Actuators [1-3] allow for high fidelity, moderate bandwidth force control. While several robots have utilized Series Elastic Actuators that use DC motors, the Monopod is the first robot that uses hydraulic versions of the actuators.
- Virtual running springs. The support phase of running is often modeled as a mass bouncing on a spring, and it is argued that the efficiency of running animals is due in part to springy muscles and tendons [4]. To both gain efficiency and simplify control, most running robots utilize a physical leg spring [5]. The Monopod is a test

platform to determine if one can use a virtual leg spring instead of a real leg spring in a running robot. With the current implementation of the Monopod, we simulate a virtual leg spring using the force-controllable properties of the Series Elastic Actuators. While we do not get the efficiency benefits of real springs, we retain control flexibility, rather than having the spring bounce fully dictate the resultant dynamics.

- High density, mobile, hydraulic power system. In order for legged robots to be practical, high power-density and high energy-density systems must be developed. Combustion-driven hydraulic systems are an appealing choice. However, lightweight off-the-shelf solutions are lacking, and expert knowledge tends to be concentrated in domains that have differing requirements than legged robots. Therefore, the Monopod is intended to be a development and test platform for mobile hydraulic power systems that can later be extended to other robots.

In the design of the robot, we used an iterative simulation-based design process. We performed physically realistic simulations of the robot running at various speeds with various total mass and extracted joint torque, speed, and range of motion requirements. Using these joint power specifications, we were able to calculate pressure and flow requirements of the system and choose individual components (pulley diameters, piston diameters, gear pump, engine, accumulator, servo valves, radiators) to meet those specifications. These components were then modeled in SolidWorks, along with the robot structure. New mechanical properties of the robot were extracted from SolidWorks to update the simulation model. This process was iterated several times until prototype design components were selected.

2. SIMULATIONS

To determine the power requirements for the monopod, we performed physically realistic dynamic simulations of the robot using the Yobotics Simulation Construction Set software. For our simulations, we assumed zero energy recapture through the use of springy legs. This is an extremely conservative assumption as springy legs provide a very large energy return in running animals and almost all running robots built to date. We plan to eventually modify the design to incorporate springy legs. However, we make the assumption of zero energy return 1) to ensure that our power system exceeds the final requirements of the robot and 2) since it is difficult to model the springy leg and determine exactly what power savings it would provide.

We developed a control algorithm for the simulated Monopod for running up to 3.5 m/s (Figure 1). The algorithm is similar to the 3-part hopping algorithm of Raibert [5], but contains a few modifications. Hopping height is controlled by controlling the vertical take-off velocity during the thrusting phase of stance, rather than through a step change in spring set point at the bottom of stance. This is possible, since the Monopod’s leg spring is virtual and arbitrary forces can be applied to the hip and knee. In contrast, the leg spring in most running robots is real and dictates much of the dynamic hopping response. Also, in addition to controlling forward velocity through foot placement, we added a speed control mechanism in which thrust is delayed if the actual velocity is less than the desired velocity.

We ran simulations at various body masses to aid in the design of the robot. While our lightweight (94 pound) simulations ran up to 3.5 m/s, our heavier simulations have only run up to 2.5 m/s to date. Figure 1 shows a stop frame animation of a 94 pound simulation running at 3.5 m/s.

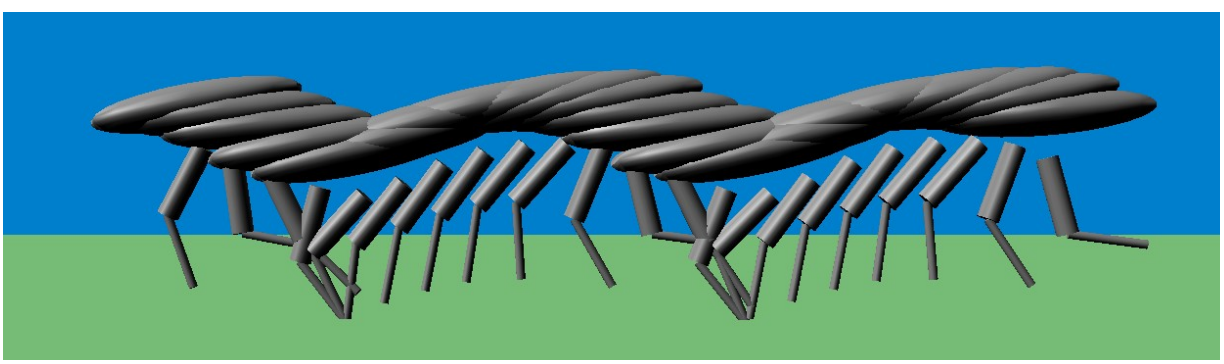

Figure 1: Stop frame animation from a 43 kg (94 pound) Monopod simulation running at a speed of 3.5 m/s. Frames are captured at 0.05 second increments. Motion is from right to left.

During running, the joint torque, speed, and power vary during a complete cycle. The maximum values for torque, velocity, power, and range of motions are shown in Table 1 for a typical simulation run. These joint power numbers were used to select components for the hydraulic system.

Table 1: Summary of Joint Power requirements from a typical simulation running at maximum speed.

Max Hip Torque	360 Nm	266 ft-lb
Max Knee Torque	360 Nm	263 ft-lb
Max Hip Velocity	24 rad/sec	224 RPM
Max Knee Velocity	28 rad/sec	264 RPM
Max Hip Power	4450 W	5.96 HP
Max Knee Power	4205 W	5.63 HP
Max Total Power	6025 W	8.07 HP
Average Power	1550 W	2.08 HP
Max Hip Rotation	1.70 rad	97.3 deg
Max Knee Rotation	1.12 rad	63.7 deg

3. HYDRAULIC SYSTEM DESIGN

Before designing the hydraulic system, we made a few assumptions regarding the overall Monopod design architecture:

1) The actuators would be mounted rigidly in the body of the robot and would be connected to the joints using a cable and pulley system. By placing the actuators in the body of the robot (as opposed to mounting them directly on the leg of the robot) we can minimize the leg mass, allowing for very fast movements.
2) The actuators would be linear, as opposed to rotary. Linear hydraulic pistons are more readily available, less expensive and are lighter than rotary hydraulic motors. Furthermore, it is difficult to implement Series Elastic Actuation using rotary actuators. This is due to the poor performance specifications of torsional springs as compared to compression springs, and due to the difficulty of instrumenting a torsional spring.

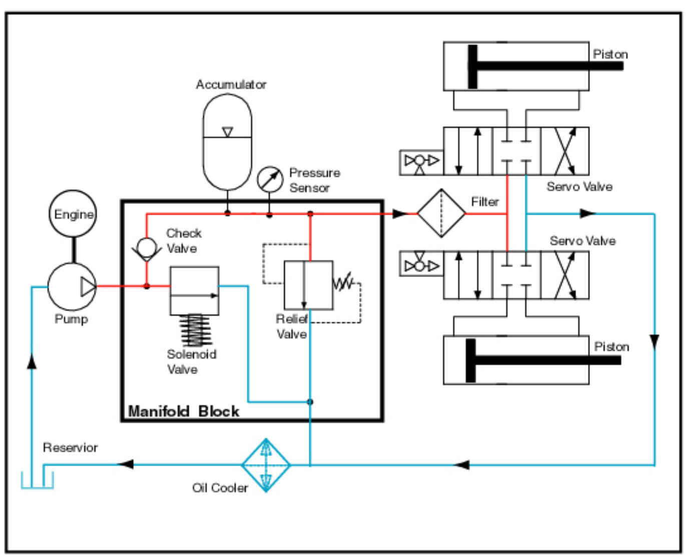

Figure 2: Hydraulic system layout for the Monopedal robot.

Figure 2 shows the hydraulic circuit designed for the Monopod. High pressure supply lines are shown in red and low pressure return lines are shown in blue. A constant displacement *pump*, driven by an *engine*, draws low pressure fluid out of the *reservoir* pressurizing and distributing the flow downstream to the *manifold block*. Once inside the *manifold block*, the flow normally passes through a *check valve* where it pressurizes an *accumulator*. Alternately, a computer controlled *solenoid valve* can shunt flow back to the *reservoir* through an *oil cooler*. This alternate path is taken when the *accumulator* has reached the maximum desired operating pressure as measured by a *pressure sensor*. High pressure fluid is stored in the *accumulator* until there is a demand from one of two *servo valves*. Alternately, if the pressure becomes too high in the *accumulator*, a *pressure relief valve* will divert flow back to the *reservoir*. The *servo valves* control the pressure and flow rates to each *piston*. As the *pistons* are cycled, return flow is sent back to the *reservoir* through the *oil cooler*, thus completing the cycle.

3.1. Hydraulic Component Selection

The hydraulic system layout is quite standard. The difficulty lies in appropriately sizing components to meet the power requirements of the Monopod without over specifying the design, which would produce excess weight. Figure 3 is a schematic representation of the component selection process.

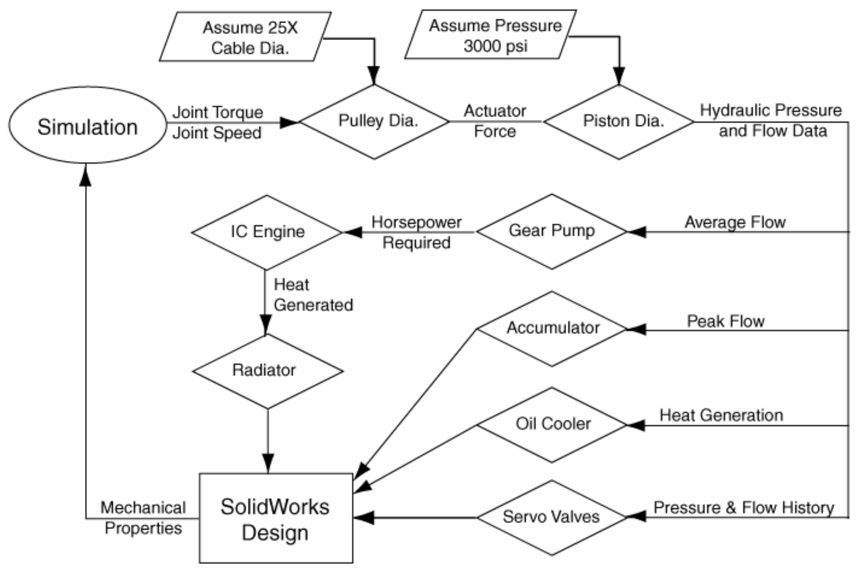

Figure 3: Diagram of simulation-based iterative design process.

3.2. Pulley and Piston Diameters

From simulations we extracted estimates of joint torques, speeds and ranges of motions for the Monopod. Power is transmitted to the joints through steel cables running over pulleys and these steel cables are actuated by hydraulic pistons. In selecting the piston and pulley diameters, we assumed an operating pressure of 3000 PSI, which is a widely accepted standard for off the shelf hydraulic components. At pressure ratings significantly higher than 3000 PSI, components become very heavy as well as exceedingly expensive.

When considering pulley diameter, one must also consider cable life. Very small pulleys produce significant bending stresses on steel cable and thus degraded cable life. According to our cable manufacturer, the pulley diameter should be about 25 times the diameter of the cable being wrapped around it. Preliminarily, we chose a .188 inches cable diameter because its breaking strength (2000lbs) appeared to be in the range we required. Using the 25X factor from the manufacturer, we arrived at a pulley diameter of 4.68 inches. For round numbers, we decided to use a 4.75 inches pulley diameter. Using this pulley diameter and 3000 PSI design pressure we calculated the required piston diameter to produce 266ft-lbs of torque to be 0.770 inches. In order to use an off the shelf item, we selected a piston diameter of 0.75 inches. Note that the actuator force (thus cable force) for the 0.75 inch diameter piston is 1324lbs, less than the rated strength of the cable of 2000lbs. With cylinder diameters of 0.75 inches and pulley diameters of 4.75 inches, the simulation produced the maximum pressures and flow rates at the actuators as shown in Table 2.

Table 2: Maximum pressure and flow rates from a typical simulation using ¾ inch piston diameter and 4.75” pulley diameter.

Max Hip Actuator Pressure	20.68 MPa	3000 PSI
Max Knee Actuator Pressure	20.68 MPa	3000 PSI
Max Hip Actuator Flow Rate	4.02e-4 m^3/s	6.38 GPM (24.5 in^3/s)
Max Knee Actuator Flow Rate	3.895e-4 m^3/s	6.17 GPM (23.8 in^3/s)
Max Total Actuator Flow Rate	6.385e-4 m^3/s	10.12 GPM (39.0 in^3/s)
Average Flow Rate	1.98e-4 m^3/s	3.14 GPM (12.1 in^3/s)

With the cylinder and pulley diameters selected, we used the simulation model to generate the pressure and flow requirements for the Monopod over and extended period of time. From this pressure and flow data we extracted the average flow, peak flow, and pressure drop. This information was then used to select the major system components including servo valves, radiator, accumulator, and gear pump.

3.3. Servo Valve Selection

Figure 4 shows the flow versus pressure history of the hip and the knee actuators during a typical simulation run, along with the flow-load characteristics of the Moog Series 32 Servo valve, with a 3200 PSI Supply Pressure. We see that if the pressure can be maintained at 3200 PSI, then the valve will be able to produce the required flow.

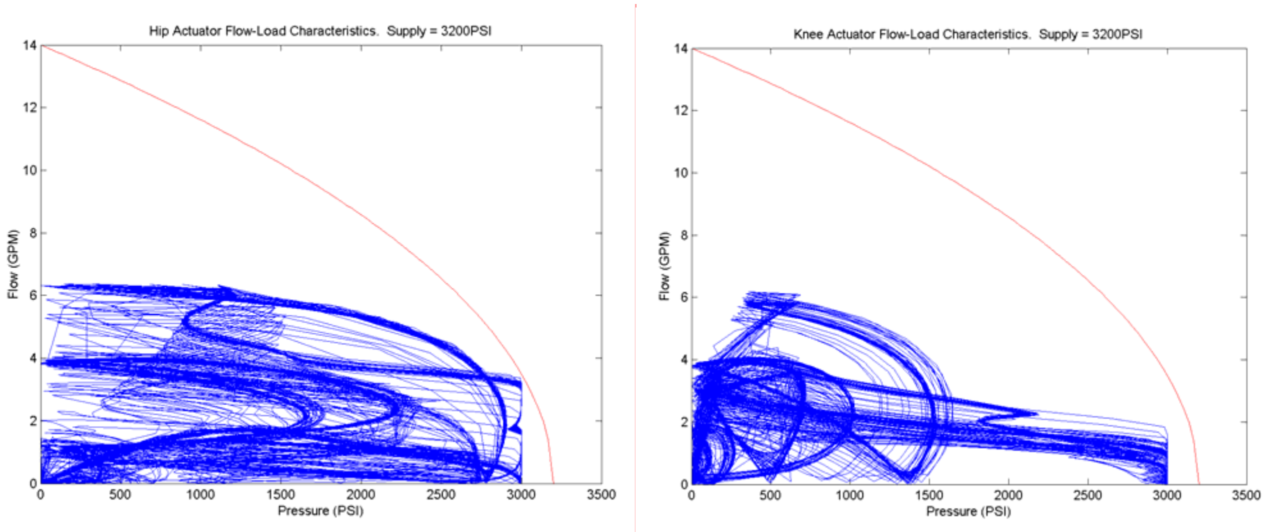

Figure 4: Hip and Knee actuator flow and load characteristics recorded during a typical simulation, compared to the fully open response of the servo valves. Both simulation curves are strictly under the servo valve curves, indicating that the estimated flows and pressures are feasible.

3.4. Accumulator

An accumulator typically uses air to act as a spring, maintaining pressure in the system. In sizing an accumulator, one needs to select the pre-charge pressure and the accumulator volume. Since the Monopod uses short bursts of energy, we assume adiabatic (no heat exchange) compression and expansion. The accumulator is pre-charged with nitrogen at pressure P_0 and has volume V_0. The minimum operating pressure is P_1 when the air volume is at V_1. The maximum operating pressure is P_2 when the air volume is at V_2.

With adiabatic expansion, we have

$$P_0 V_0^{1.4} = P_1 V^{1.4}{}_1 = P_2 V_2^{1.4}$$

We can solve for V_1 and V_2 in terms of V_0:

$$V_1 = \left(\frac{P_0}{P_1}\right)^{1/1.4} V_0, \quad V_2 = \left(\frac{P_0}{P_2}\right)^{1/1.4} V_0$$

Subtracting and solving for V_0, we get

$$V_0 = \frac{V_1 - V_2}{\left(\frac{P_0}{P_1}\right)^{1/1.4} - \left(\frac{P_0}{P_2}\right)^{1/1.4}}$$

Parker-Hannifin recommends that the pre-charge pressure be 90 percent the minimum pressure. However, to ensure that the system pressure never falls below pre-charge, we set it a little below that. If we set the minimum pressure to 3000 PSI, the maximum to 3400 PSI, and the pre-charge pressure to 2500 PSI, then we get

$$V_0 = 13.3(V_1 - V_2)$$

To sustain the maximum combined flow rate of 10.12 GPM over the contact period of 0.2 seconds, we need an accumulator volume of 0.854 gallons (1.7 Liters) with these values. To be conservative, we chose a 2.0 Liter accumulator, which should be able to sustain 0.2 seconds of max flow at over 3000 PSI if we charge it to at least 3400 PSI. This choice also provides 2.9 seconds of operation at our average flow rate of 3.14 GPM.

3.5. Pump

The average flow rate of the system is calculated by integrating the absolute values of the flows over the hip and knee, and dividing by time. Our pump needs to supply the average flow rate of 3.14 GPM at the maximum pressure of 3400 PSI. To be conservative and account for losses, we selected a constant displacement pump rated at 3.5 GPM at 3500 PSI.

3.6. Internal Combustion Engine

The chosen pump needs a continuous input power of 7.2kW (9.65 HP) to conservatively drive 3.5GPM, 3500PSI. Because of its high power density, we chose a two cycle engine over a four cycle engine. In an effort to further reduce weight, we chose a 16 horse power, 150cc hobby aircraft engine designed specifically for “giant scale” hobby aircraft. The engine was oversized in an effort to avoid a condition of maximum load 100% of the time. Because of its use in model aircraft, the engine we chose was air cooled.

As one would expect, a tremendous amount of heat is generated by the high RPM two stroke engine. This heat must be removed to prevent seizing of the pistons. Since the Monopod was not expected to achieve the speeds of hobby aircraft (upwards of 120mph) we knew air cooling would be a challenge. Several tests were performed to determine if air cooling would be possible using on board fans or blowers. We determined that it would be very difficult to achieve air cooling under our load conditions and therefore decided to liquid cool the engine.

In order to liquid cool the engine, the cylinder heads were modified to accept liquid tight jackets. Next, we devised a test to measure the amount of heat generated by the combustion engine. This information would be required to properly size a radiator to remove the heat from the coolant. During the tests, the engine was cooled by a reservoir containing four liters of water, which was circulated through water jackets encapsulating the cylinder heads. The temperature of the reservoir was measured and recorded once every 60 seconds. The results of two tests (one under light load and one under heavy load) can be seen in Figure 5 below.

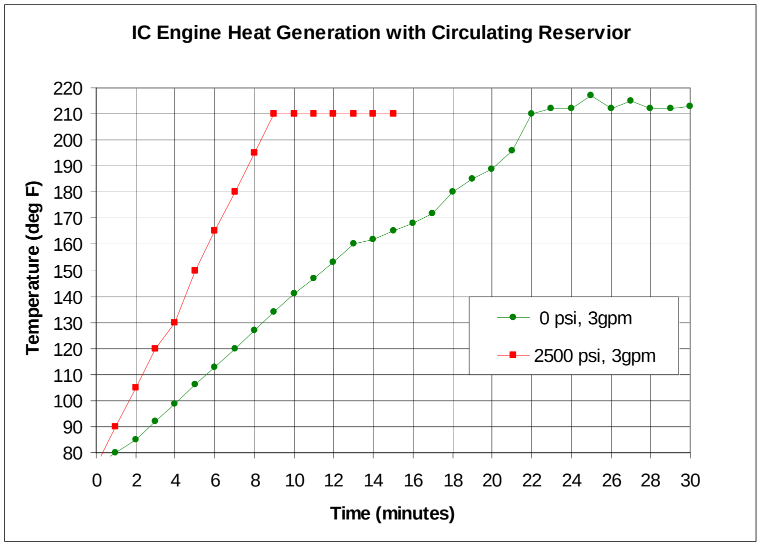

Figure 5: Heat generation of two cycle, 16 horsepower, 150cc hobby aircraft engine. Engine cooling was achieved by circulating four liters of water, in a closed loop, through water jackets encasing the cylinder heads. Tests were conducted under hydraulic loads of 0 PSI at 3 GPM and 2500 PSI at 3 GPM (4.4 horsepower).

Using the Specific Heat of water, the mass of the water, change in temperature and time, we can calculate the power generated to heat water according to Equation 1, where the specific heat of water is 4.19 Joules/gram°C. From this data and Equation 1, we found that the approximately 1021 Watts of heat is generated at 0 PSI, 3 GPM while 2322 Watts of heat is generated at 2500 PSI, 3 GPM.

$$Power(Watts) = \frac{SpecificHeat\left(\frac{Joules}{grams^{\circ}C}\right) \times Mass(grams) \times \Delta T\left({}^{\circ}C\right)}{\Delta t\ (\sec onds)}$$

(Equation 1)

It should be noted that tremendous amounts of heat can be removed from this system by vaporizing the water. Once the temperature reaches the boiling point, the formula changes to that shown in Equation 2, where the heat of vaporization of water is 2260 J/gram. Thus, heating water from room temperature to boiling (80°C temp change) requires approximately 335 Joules per gram, whereas evaporating the water requires 2260 Joules per gram, or about 6.7 times more energy. Naturally this leads one to believe that evaporative cooling might be a good approach. However, in evaporative cooling, you are limited by the amount of water you carry on board. For this reason, we choose a more conventional approach: using a radiator to prevent the water from boiling.

$$Power(Watts) = \frac{Heat\ of\ Vaporization\left(\frac{Joules}{grams}\right) \times Mass(grams)}{\Delta t(\sec onds)}$$

(Equation 2)

From the two test conducted above, it is clear that we can cool the engine using a circulated water cooling method if we are able to remove approximately 2500 Watts of energy from the coolant. If the outside temperature is 32°C (90 F) and we assume that the operating temperature of the water cooler is 225°F (107°C). (250°F is possible with a 50% water 50% Ethylene Glycol mixture), for a difference of 75°C, then we need 35 W/°C cooling rate for the water. A radiator meeting these specifications was chosen, along with a circulating pump to move water through the closed loop. The temperature vs. time history of two load conditions with water cooling through the chosen radiator can be seen in Figure 6.

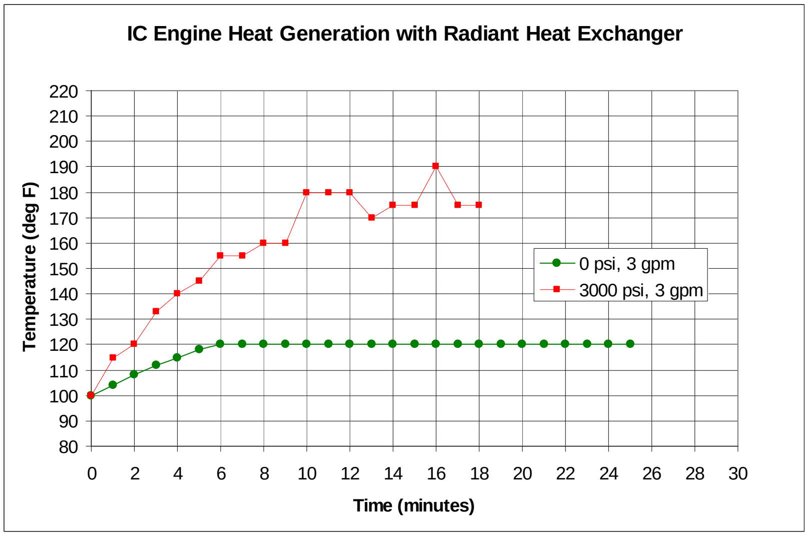

Figure 6: Heat generation of two cycle, 16 horsepower, 150cc hobby aircraft engine. Engine cooling is achieved by circulating a 1:1 mix of Ethylene Glycol and water in a closed loop with an air cooled radiator. Tests were conducted under hydraulic loads of 0 PSI at 3 GPM and 3000 PSI at 3 GPM (5.3 horsepower).

3.7. Hydraulic Heat Generation and Removal

Primarily due to the large pressure drops over the servo valves during high speed, low force motions, there will be large amounts of power dissipated into the hydraulic fluid. Simulation results show approximately 2600 Watts of average heat generation while running at speeds between 1.5m/s and 3.5 m/s. We need to remove this heat from the system to prevent overheating. If the outside temperature is 32 C (90 F) and the oil temperature is 79.4 C (175 F), or a difference of 47.4C, then we need 52.7 W/C cooling rate for the oil. A radiator meeting these specifications was chosen.

3.8. Reservoir

Reservoirs in hydraulic systems are important for allowing air bubbles to come out of the fluid and for allowing particles to settle. Various hydraulics applications engineers that we spoke to recommended a minimum reservoir size of one minute of fluid flow. However, for the Monopod that would require an approximately 3.5 gallon reservoir at a weight of 28 pounds. Therefore, we performed some tests using an off-board hydraulic system and ran hydraulic fluid through a pressure relief valve and radiator at 3500 PSI, 3.5 GPM with approximately 1.5 gallons of fluid in the reservoir. After 15 minutes, there were no noticeable bubbles and we determined that 20 seconds of fluid flow may be acceptable for our application.

3.9. Series Elastic Actuators

Series Elastic Actuators [1-3] provide many benefits in force control of robots in unconstrained environments. These benefits include high force fidelity, low impedance, low friction, and good force control bandwidth. Series Elastic Actuators employ a novel mechanical design architecture which goes against the common machine design principal of “stiffer is better”. A compliant element is placed between the gear train and driven load to intentionally reduce the stiffness of the actuator. A position sensor measures the deflection, and the force output is accurately calculated using Hooke’s Law (F=Kx). A control loop then servos the actuator to the desired output force. The resulting actuator has inherent shock tolerance, high force fidelity and extremely low impedance. These characteristics are desirable in many applications including legged robots, exoskeletons for human performance amplification, robotic arms, haptic interfaces, and adaptive suspensions.

The Monopod is the first legged robot that uses hydraulic Series Elastic Actuators. A CAD model of the actuator design is shown in Figure 7. Four pre-compressed die compression springs lie between the hydraulic piston and the output. A linear encoder measures the spring deflection, which is used in a PI force-control loop implemented in software and updated at 1000 Hz. This actuator produces over 1300 pounds of force, with a force-control bandwidth of approximately 40 Hz.

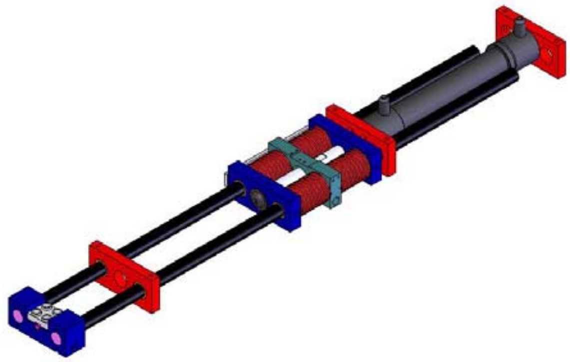

Figure 7: CAD model of hydraulic Series Elastic Actuator used in the Monopod.

4. MECHANICAL DESIGN

The body of the robot consists of two 1/8th inch thick carbon fiber plates separated by aluminum cross members for rigidity. Individual components specified above are mounted between the carbon fiber plates. The center of mass of the robot is approximately 12 inches directly above the hip joint. The upper and lower legs consist of four 1" diameter carbon fiber tubes which are permanently mounted to machined aluminum joints using high strength epoxy. The center of mass of each leg falls just above the mind point of the link. A SolidWorks model of the final mechanical design, including overall dimensions and primary system components is shown in Figure 8. Figure 9 shows photographs of the completed Engine-Pump Assembly as well as the complete Monopod Robot.

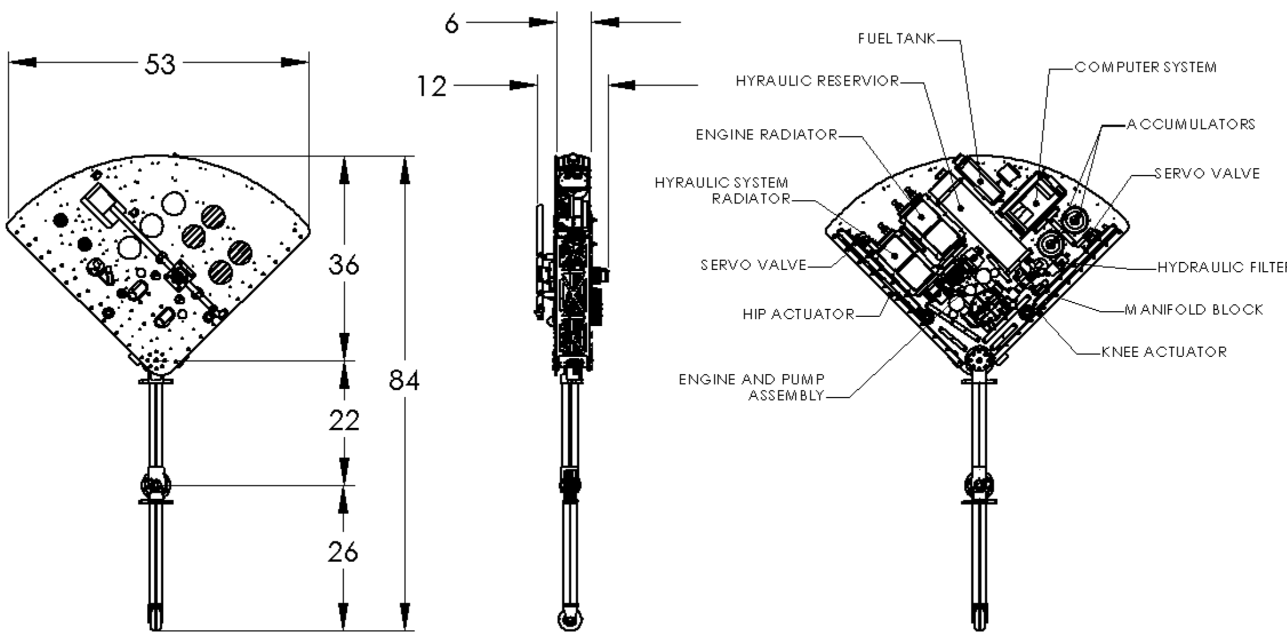

Figure 8: SolidWorks design drawings showing overall size of the Monopod and layout of major components. Units are in inches.

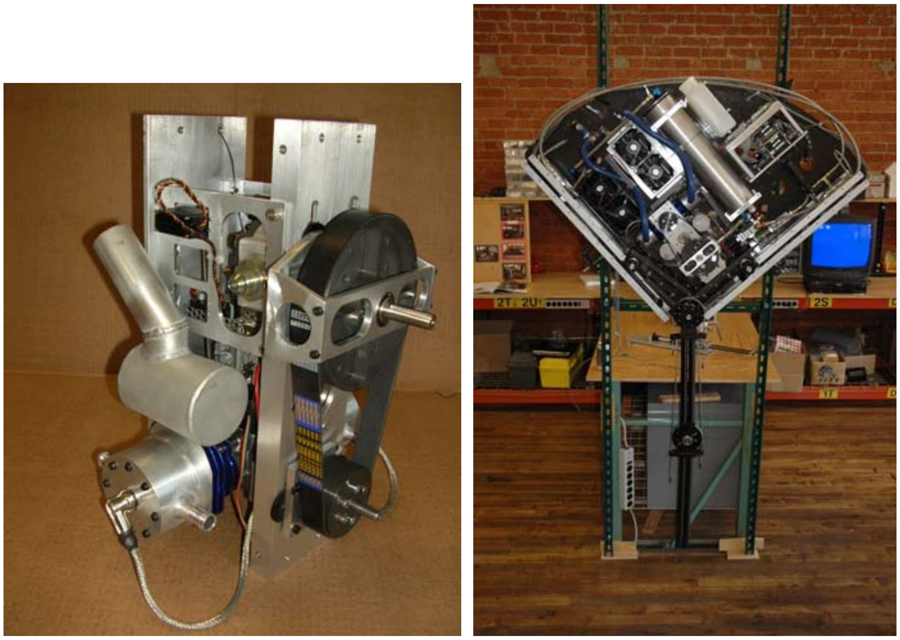

Figure 9: Photographs of completed engine and pump assembly (left) and Monopod with carbon body plate removed (right). The engine and pump assembly has a total dry weight of 22lbs. and is capable of hydraulic pressure up to 4000 PSI at 4.5 GPM which is equivalent to 10.5 horsepower. Pressure and flow rate are limited by gear pump specifications. The total dry weight of the Monopod is 115 pounds. With hydraulic fluid, engine cooling fluid, and gasoline, the full weight is approximately 125 pounds.

5. PRELIMINARY RUNNING RESULTS

The Monopod currently runs at approximately 1.2 m/s with the weight of all the power generating components, but powered from an off-board pump. Video images are shown in Figure 10, while data is shown in Figure 11. On a test stand, the eventual on-board power system generates enough pressure and flow to meet the requirements of these runs and we are currently integrating the power system into the real robot. When operated from an off-board system without carrying the weight of the power generating components, the robot currently runs at approximately 2.25 m/s. The control algorithm used for both weights was identical, indicating that with further algorithm development we should be able to achieve faster and more efficient running.

Figure 10: Monopod running with full component weight of approximately 125 pounds, but powered from off-board hydraulic source. Images are spaced at 0.1 seconds. Robot runs from left to right.

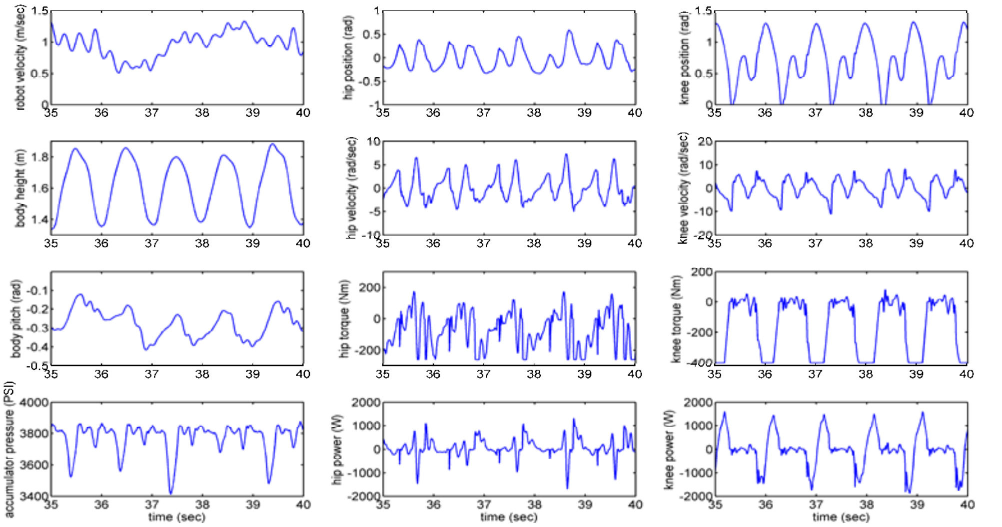

Figure 11: Data from the Monopod running with full component weight of approximately 125 pounds, but powered from an off-board hydraulic source. The leftmost graphs show robot velocity, body height, body pitch, and accumulator pressure. The middle graphs show hip position, velocity, torque, and mechanical power. The right graphs show knee position, velocity, torque, and mechanical power.

6. DISCUSSION: HYDRAULIC SYSTEMS AND EFFICIENCY

We chose the hydraulic system layout shown in Figure 2 due to the high power densities we could achieve and the low complexity. However, with our application, using a single accumulator charged to a high pressure is extremely inefficient. Particularly, during high speed, low force motions, there is a high flow rate out of the accumulator and high pressure drop over the actuator servo valves, generating large amounts of heat. In fact, given the same amount of actuator stroke motion, a low force motion, such as leg swing, requires the same energy as a high force motion, such as stance. Since running requires alternating periods of high force and low force motions, this hydraulic system layout is ill suited to running robots if efficiency, and hence time between refueling is important.

Despite these inefficiencies, many robots and exoskeletons [5-7] use similar hydraulic layouts where a single accumulator is charged to a high pressure. The main reasons are low weight, low complexity, and high bandwidth. However, time between refueling of these systems may be too frequent for practical use.

Song, Waldron and colleagues [8] recognized the low efficiency of single pressure valve-controlled systems during the design of the Adaptive Suspension Vehicle. To avoid these inefficiencies, they instead opted for a hydrostatic system in which each actuator has a variable displacement pump. All of the pumps are driven by a single engine and their displacements are controlled by swashplate control actuators. Despite requiring motion of significant swashplate masses, they reported position control bandwidths up to 20Hz. They also investigated several other alternatives, including drawing flow from multiple pressure sources, depending on the demands of each actuators. They rejected that possibility due to the required addition of extra hydraulic lines and manifold blocks, and the extra servo valves required.

Except for the cost of the extra servo valves (approximately $4000 each), we think that a multi-pressure system may be an attractive option. A single engine could drive either multiple pumps or a variable displacement pump which pressurizes each of the accumulators depending on their need. Each actuator could pull from any of the accumulators through a network of switches. If there were M pressures, M-1 switches would be required per actuator (the lowest pressure source could always be connected). For N actuators, (M-1) * N switches plus N servo valves would be required. From results with the Monopod, we believe as little as 2 or 3 supply pressures could result in significant efficiency gains. While the switches could be implemented with the same high performance servo valves, their requirements are much less demanding and could potentially be implemented with lower performance valves such as on-off solenoid valves. For running, we estimate on the order of 0.05 to 0.1 second switching time could be sufficient, especially since it is straightforward to predict when high pressure will be required and the switches could be switched ahead of time.

The potential to switch between supply pressures at high rate leads one to ponder whether a switching circuit similar to a PWM electric motor amplifier could be developed. However, there are two key requirements of PWM circuits that allow them to be efficient: high frequency switches and inductors. With an electric PWM motor amplifier, high voltage is applied momentarily through a switch to an inductive load. The inductor builds up its magnetic field and when the switch turns off, the electric field breaks down, causing current to continue flowing through the load. Since the switching frequency, typically on the order of 10 kHz, is an order of magnitude faster than the L/R time constant of the load, the current delivered to the load smoothly varies. With such a circuit, a single high voltage source can be used to efficiently drive a load with varying voltage requirements.

Unfortunately, hydraulic switches are relatively low frequency, on the order of 100 Hz, and hydraulic inductors are impractical. While there is some inductance (inertia) in the hydraulic fluid itself, it is not sufficient. One could make a hydraulic inductor using for example a hydraulic motor with a flywheel, but the size and weight may be prohibitive. For high inertial loads, the mass of the load may provide the proper amount of inertia and such a technique might be practical. However, the loads present during the periods of concern for a running robot (such as leg swing) are typically very low inertia. Therefore, it is doubtful that similar techniques to PWM amplifiers can be used in hydraulic circuits unless new forms of small and lightweight hydraulic inductors and faster hydraulic switches can be developed.

7. NEXT STEPS

Ongoing efforts with the Monopod include the following:

- Finish integrating the power system into the Monopod.
- Further refine the control algorithm.
- Investigate more efficient hydraulic system designs.

8. ACKNOWLEDGEMENTS

This project was funded under TACOM SBIR contract #W56HZV-04-C-0072. Special thanks to Gill Pratt for clarifying discussions on the operation of electric PWM amplifiers.

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