DEVELOPMENT OF A LIGHTWEIGHT ON-BOARD HYDRAULIC SYSTEM FOR A QUADRUPED ROBOT

Hamza Khan, Satoshi Kitano*, Yifu Goa, Darwin G. Caldwell, Claudio Semini
Department of Advanced Robotics, Istituto Italiano di Tecnologia.
Genova, Italy.
E-mail (iamhamza@me.com, hamza.khan@iit.it)
Department of Mechano-Aerospace Engineering, Tokyo Institute of Technology.*
Tokyo, Japan.*
E-mail (kitano.s.ac@m.titech.ac.jp*)

Abstract
This paper presents the development of an on-board power pack for a highly dynamic and lightweight hydraulic quadruped robot called MiniHyQ. It is a torque-controlled quadruped robot able to walk over rough terrain, jump and run. The compact power pack is designed to fit inside MiniHyQ's torso section. The hydraulic power source is provided by an on-board miniature gear pump, which is driven by a high torque brushless motor. The selection of each appropriate component of power pack is discussed in detail. A step-by-step procedure is proposed which demonstrates how to design of the power pack for a quadruped robot in order to obtain the desired performance. A centralized compact and lightweight manifold design is also presented which works at 20 MPa operating pressure.

KEYWORDS: Hydraulic Quadruped robots, Miniature Hydraulics, Hydraulic Power Pack

1. INTRODUCTION

The hydraulic actuators are very favorable for the highly dynamic robots because of their higher torque and smaller size than the electric motors. Most of the current research platforms in legged robotics are hydraulically actuated. The hydraulic actuation provides them strength and fast motions to perform dynamic tasks. The majority of the successful platforms are hydraulically powered as opposed to electrically actuated, for example, WildCat and BigDog [1] from Boston Dynamics and HyQ [2] from IIT. Hydraulics has the significant advantage of being able to absorb high impact loads (no gears required), having a high power to weight ratio and allowing the implementation of high performance torque control [3]. For producing the desired hydraulic actuator's joint torque, it is essential to have a hydraulic power pack which supplies needed pressure and flow rate. But having an on-board hydraulic power pack is a burden to a legged robot. It is not only increase a weight of a robot but also raise the joint torque requirements. To reduce the weight of the hydraulic power pack, we built a highly dynamic and lightweight hydraulic quadruped robot MiniHyQ. To the authors' best knowledge, MiniHyQ is the lightest and smallest hydraulic quadruped robot that has been built so far. The weight of the hydraulic power pack is in proportion to the supply pressure and the supply flow. So the velocity of the hydraulic actuator should be reduced for reduction of a supply flow. MiniHyQ uses a special mechanism [6] for its knee joint which has tendency to produce high velocity when its leg is fully extended. This knee joint helps MiniHyQ to reduce its actuator velocity during the leg in swing phase and it also minimizes the flow rate consumption.

T. Kim et al. proposed and experimentally validated the algorithms [15] which uses the kinematic redundancy of each leg mechanism for a hydraulic quadruped robot to minimize the flow rate consumption. He demonstrated that the reduction in actuator velocity by using leg kinematic redundancy reduces the weight of the hydraulic power pack up 34% [15].

In the case of other hydraulically actuated quadruped robots like BigDog [1] monopedal robot [10], and JINPOONG [12], they have a combustion engine to actuate the pump inside the torso. However, with combustion engine it is difficult to conduct experiments indoors, because of the noise and the exhaust fumes. Normally for indoor experiments, the external electric pump is used. It supplies hydraulic power to the robot by means of two hydraulic hoses. These hoses can negatively affect the dynamics of the robots causing unpredictable disturbances and restricting the working range of robot in a circumference around the pump. Therefore, we decided to develop on board hydraulic system with electric pump for MiniHyQ. By using the electric motor, the robot needs only electric wire which is more flexible and less affect motion of the robot. Although the robot can be power autonomous by putting a battery on the robot, we focused on wired system in consideration of weight of the battery. This kind of on board hydraulic system is already adopted to Atlas humanoid robot and Baby elephant [14].

The motivation for this work arose from the experience of our group (the Dynamic legged systems (DLS) lab) with the quadruped robot HyQ [2] shown in Figure 1 (*left*), which leads us to build MiniHyQ which can be seen in Figure 1 (*right).*

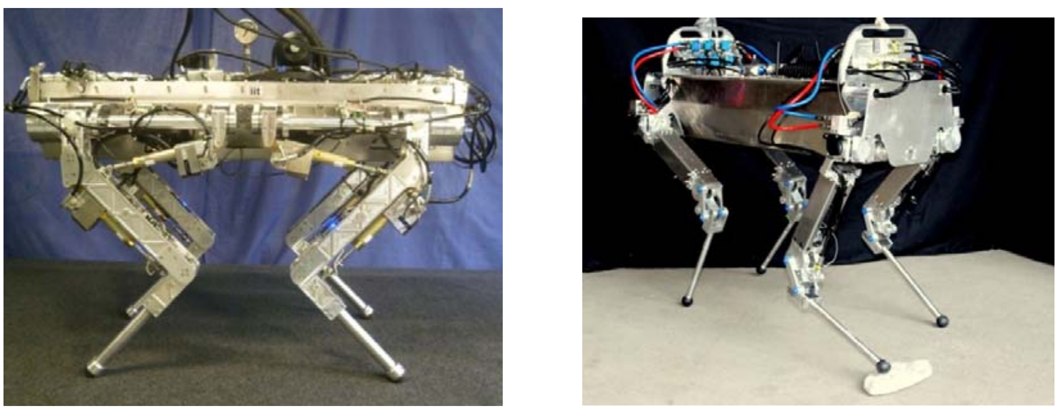


Figure 1. The DLS lab robots (left)the HyQ Robot; (right) the MiniHyQ Robot

Contributions:

The main contribution of this work is the development of an on-board power pack for a lightweight hydraulic quadruped robot-MiniHyQ. To the authors' best knowledge, MiniHyQ is the lightest and smallest hydraulic quadruped robot that has been built so far. We demonstrated the design of the power pack which fits inside MiniHyQ's torso section and a step-by-step procedure is proposed which demonstrates how to design the power pack for a quadruped robot in order to obtain the desired performance. In order to keep MiniHyQ legs as lightweight as possible, a centralized manifold is placed in torso rather than using distributed manifolds on each leg.

Paper Outline: The paper is structured as follows: first, an overview MiniHyQ design is discussed in Section 2 and it includes the description of the MiniHyQ's control system; next, Selection of each component of the MiniHyQ's hydraulic system is demonstrated in Section 3. Section 4 discusses the power pack and concludes the paper.

2. MINIHYQ ROBOT

This section presents an overview of MiniHyQ's design [16] and its control system architecture. Table 1 shows the specification of MiniHyQ. Each leg is driven by 3 hydraulic actuators. We selected these actuators based on our scaling studies [4][5]. In these studies, we considered extreme tasks that push the actuators to their limits. This gives us a good estimation of the joint torques and velocities necessary to select the leg actuators. MiniHyQ has a 0.85m long torso as shown in Figure 4 (right). It is made of 2 mm thick folded aluminium sheet and contains the computing system, IMU (inertia measurement unit) sensor, hydraulic manifolds and compact power pack. Hip Flexion/Extension (HFE) and Knee Flexion/Extension (KFE) are the joints, which work in leg-sagittal plane. They are responsible for generating the main forward and upward motion of the robot. Most tasks like straight walking and running on flat terrain are accomplished by these joint. Rotary hydraulic actuators have wide range of motion and constant torque. However, they are heavier than linear actuator. For MiniHyQ's HFE joint, we used a rotary actuator. But if we put rotary actuator inside the KFE joint, it would increase the inertia of leg significantly. Therefore, for KFE we used linear actuator with special knee mechanism [6], which does not only provide wider range of motion but also provides an optimized torque profile. The third joint named as hip Abduction/Adduction (HAA) is less involved in the creation of forward propulsion. Linear actuators are also used for the HAA Joint. CAD Model of MiniHyQ's leg design is shown in Figure 2.

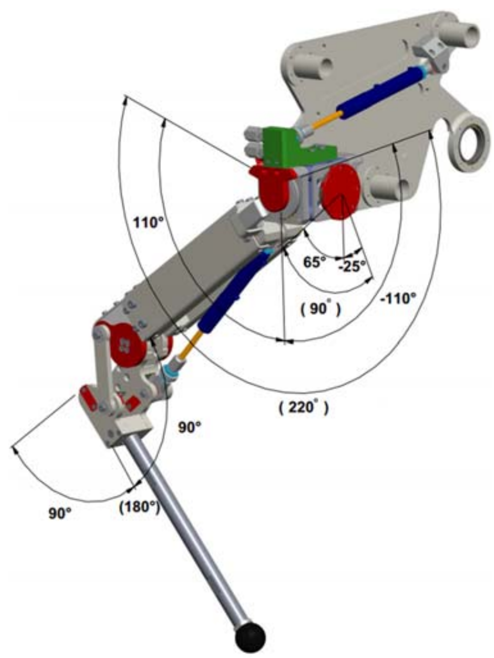


Figure 2. CAD model of MiniHyQ Leg which is consist of 3 active DoF i.e HAA, HFE and KFE joints.

Hip Abduction/adduction (HAA) is important joint of a quadruped robot to support robot's weight (mostly in case when robot legs are not parallel to its leg-sagittal plane). HAA joint always needs to react quickly to keep robot's balance. It requires a reasonable joint torque and velocity. An asymmetric hydraulic cylinder is used, which has a bore diameter of 13mm and a rod diameter of 6mm with 69 mm stroke length. It weighs 0.11kg and one end of cylinder is attached on the top surface of Hip Flexion/Extension (HFE) joint motor and other end is attached to torso plate as shown in Figure 2.

Hip Flexion/Extension (HFE) joint is based on hydraulic rotary actuator. It has joint range of motion of 220°(-110° to 110°) and it provides constant joint torque 60 Nm at 20MPa.

Knee Flexion/Extension (KFE) is based on an isogram mechanism, we proposed in [6]. It has a changeable instantaneous center of rotation like a human knee joint. We optimized a set of design parameters to obtain a smoothly distributed torque profile that provides high torque in a retracted joint configuration (i.e. flexed leg) and high velocity (but lower torque) when approaching the fully extended configuration. Furthermore, a large knee joint range q from 0 to 180°.

Table 1. Specifications of MiniHyQ Robot

Dimensions (LxWxH)	0.85m x 0.35m x 0.7m
Weight (off-board/on-board Power Pack)	24kg, 35kg
Degrees of Freedom	12 (3 per leg (2-linear1-rotary hydraulic actuator))
Joint Torque/ Range of motion	75 Nm,90° HAA 60 Nm, 220° HFE 75 Nm,180° KFE
Sensors per Leg	2 Load cells, 1 Torque sensor 3 Absolute encoders
Hydraulic Valves	12 High performance servo valves (Moog E024)
On-board Computing	1 computer (real time Linux)
Operating Pressure	20 MPa
Peak Flow Rate	13 l/min

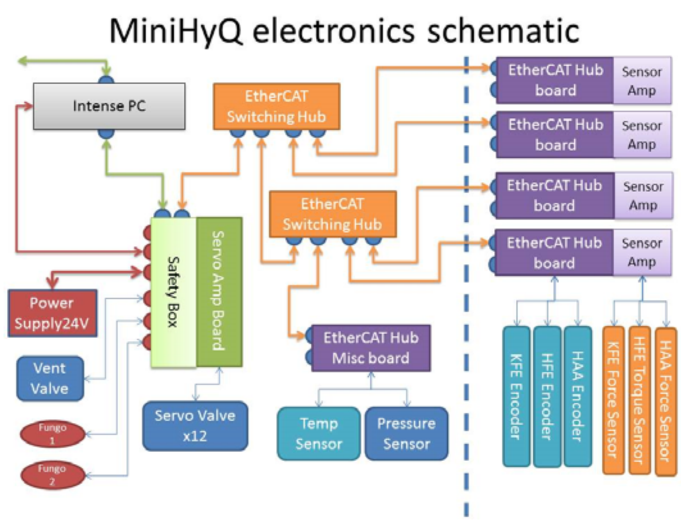


Figure 3: *MiniHyQ's control system architecture*

The control system architecture of MiniHyQ is shown in Figure 3. It basically consists of a main unit and 4 leg units.In the main unit, control PC running Linux kernel patched with real-time Xenomai takes care of all low level control of servo valves via main I/O board and high level control such as leg trajectory. Leg unit collects input signal from 3 magnet encoders (19 bit, absolute type), 2 force sensors (±4448N) and 1 custom designed torque sensor, and sends these data to the main unit. For communication between each unit, EtherCAT bus is used and gives the system high speed real time communication. As a low level controller, each joint is fully torque controlled based on the HyQ's torque controller [7]. Full torque control allows the robot to perform active compliance which is essential to cope with impacts during dynamic motions. Furthermore inverse dynamics can be used for improving control of locomotion [8].

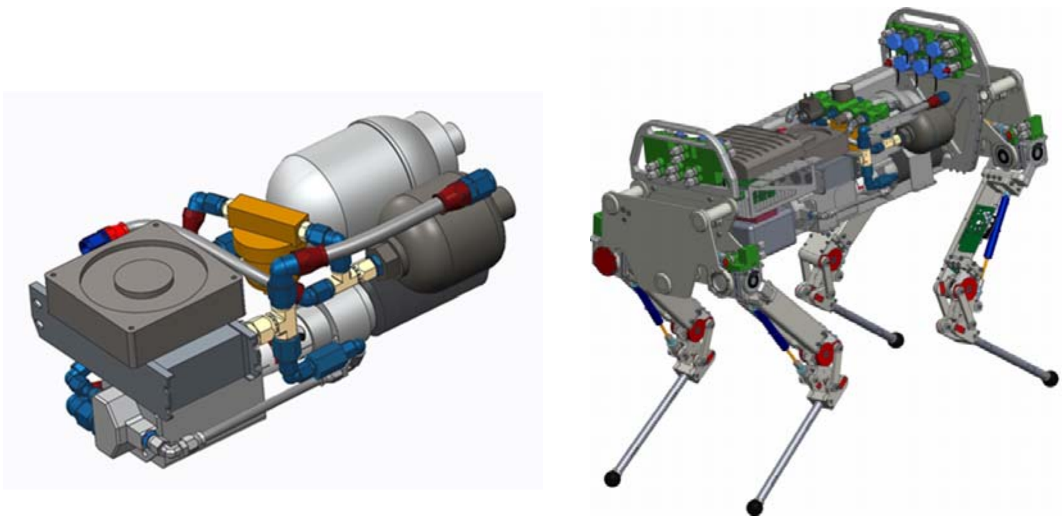


Figure 4. *The CAD model of MiniHyQ with exposed view of onboard power pack, magnetic encoder disks and EtherCat control PCB in upper leg link.*

3. DESIGN OF THE HYDRAULIC SYSTEM FOR MINIHYQ

In this section, we explain the step by step design procedure of the hydraulic system of MiniHyQ. Table 2. shows the specification of the designed power pack and *Figure 5.* shows the schematic of hydraulic system of MiniHyQ. It consists of a miniature pump, an electric motor, manifolds, vent valve and relief valve for safety. This power pack is detachable and it can be replace by an external pump if it is available. Before designing hydraulic system, the maximum pressure of hydraulic system was decided by the actuators desired operating pressure, which is 20 MPa. In following design we use this value as maximum pressure.

Table 2. Specification of power pack MiniHyQ

	MiniHyQ Power Pack
Size(L x W x H)	0.59 x 0.20 x 0.19 m
Weight	12 kg
Rated flow rate	10 L/min
Max System Pressure	20 MPa
Max Power Consumption	5.5 kW

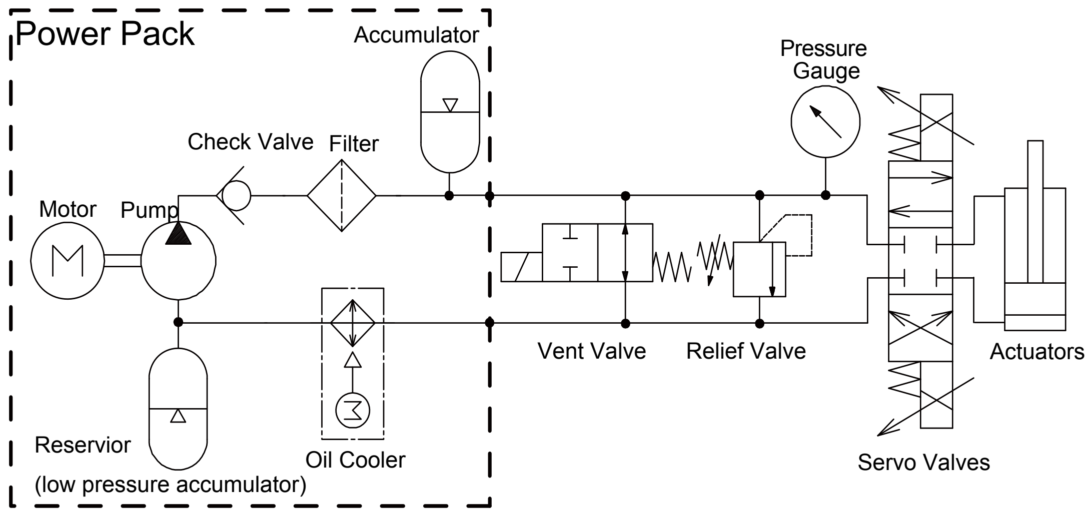


Figure 5. Schematic of Hydraulic system

3.1. Estimation of required flow rate

First of all we estimated the required flow rate for the each actuator. In order to estimate required flow rate, we used the experimental data of previous quadruped robot HyQ[2]. Since MiniHyQ and HyQ have almost same length of leg segments, we assumed that required angular velocity of each joint is same for MiniHyQ and HyQ. As a template motion which determines the maximum performance of the robot, 2m/s running trot and 0.2 m squat jump were chosen. As we explained in section 2, MiniHyQ has different leg mechanism comparing to HyQ. Required flow rate for each joints are calculated by multiplying required angular velocity and volumetric displacement of each actuator. In case of rotary actuator for HFE, volumetric displacement is constant. However in case of linear actuator with linkage mechanism for HAA and KFE, volumetric displacement varies with each position and the volumetric displacement is calculated by inverse kinematics. Figure 6 shows the sum of the required flow rate of all of the actuators and the leakage flow of servo valves.

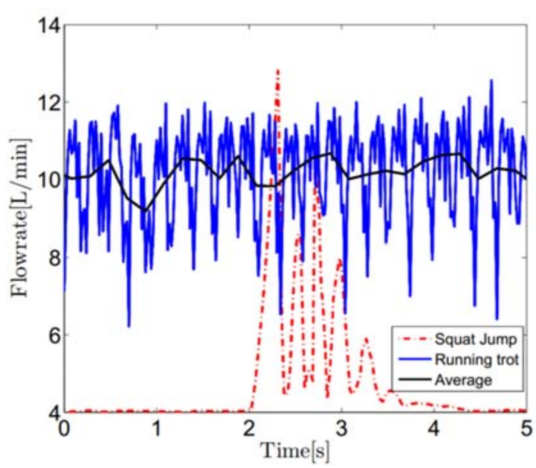
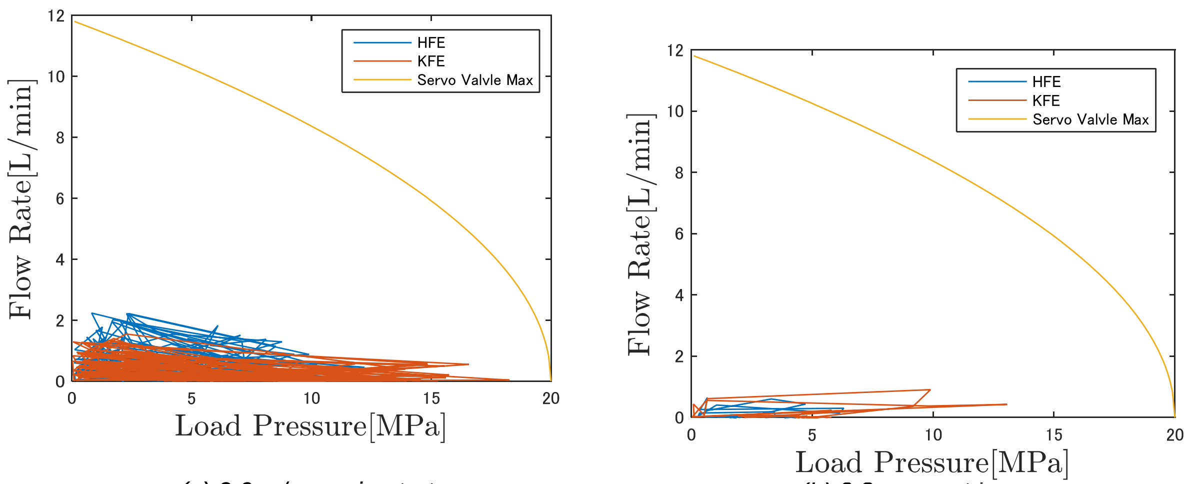


Figure 6. Estimated flow rate, blue line shows the total required flow rate of the robot while Running trot, red dotted line shows the total required flow rate while Squat Jump, and black line shows the average flow rate while Running trot.

3.2. Selection of Servo Valve

In order to control the dynamically walking of a robot such as the MiniHyQ, high-bandwidth performance is the most important for torque control. In this case, we choose MOOG E024 nozzle flapper type servo vale whose dynamic performance is 250Hz. This servo valve is also used for the HyQ robot. In order to verify selected servo valve can control the flow and pressure while template motions, Figure 7 shows required flow rate versus load pressure of HFE and KFE joint actuator (HAA is excluded because it is not dominant for running trot and squat jump) which were calculated above and the flow-load characteristic of the Moog E024 servo valve at fully open. As shown in the graph, at all of the operating point, flow rate and load pressure are under the performance of the servo valve at fully open.



(a) 2.0 m/s running trot *(b) 0.2 m squat jump*

Figure 7. Verification of servo valve performance

3.3. Selection of a pump and an electric motor

The most important points of a power pack for a mobile robot is lightweight. In order to achieve lightweight, a high power weight ratio electric motor and lightweight pump is used which fulfill the required specification estimated above (average flow rate 10L/min, system pressure 20Mpa).

Main problem of selecting pair of an electric motor and a pump is mismatching of required speed and torque, even though motor output power and pump output power is same. Nowadays it is not difficult to find a high power weight ratio electric motor. However such high power is only obtained at high speed region and low torque region. On the other hand required output power of a pump is decided by its differential pressure, volumetric displacement and maximum input speed. Volumetric displacement can be choose, but maximum input speed is limited by a sealing. To solve this problem, two ways are considered. First one is introducing a gear reduction mechanism to change ratio of torque and velocity. Downside of this way is decreasing power weight ratio because of increasing of total mass and there is energy loss which indicated as efficiency. Thus big reduction ratio should be avoided. Second solution is selecting as much as small volumetric displacement pump to fulfill the required flow rate. As shown in below equation, required input torque is decreased proportionally to volumetric displacement. V_g is volumetric displacement per rotation [cm^3], ΔP = differential pressure [MPa], η = efficiency of a pump.

$$T_{input} = \frac{V_d \cdot \Delta P}{2\pi \cdot \eta} \quad (1)$$

Unlike introducing the gear reduction mechanism, volumetric displacement is basically does not change allowable input speed. Thus to keep its output power required input speed have to be increased inversely proportional to volumetric displacement.

Considering above 2 points we choose an electric motor and a pump from available consumer products. According to Figure 6, required average flow rate what a pump needs to supply is 10 L/min, and the maximum hydraulic pressure is 20 MPa. To achieve this specification with minimum volumetric displacement, we choose small size axial piston pump with constant volumetric displacement made by TAKAKO (maximum operating pressure 21MPa, maximum input speed 3000rpm, volumetric displacement 3.15 [cm^3], weight 1.94 kg). Actually its rated flow rate from the specification is 9.15 L/min, but we consider required average flow rate 10 L/min is not always required and in short time operation the pump could rotate at 3300 rpm to achieve 10 L/min. Otherwise we have to choose another pump which has double volumetric displacement and it requires too much torque to the motor. As a high power weight ratio electric motor, brushless DC motor originally designed for a hobby air plane by Neu motor (maximum output power 10kW, weight 1.36kg) and 1 stage planetary gear box (reduction ratio 6.5, weight 0.43kg) was choose. Additionally the motor contains cooling fan internally to keep its working temperature. The chosen pump and motor are shown in Figure.8.

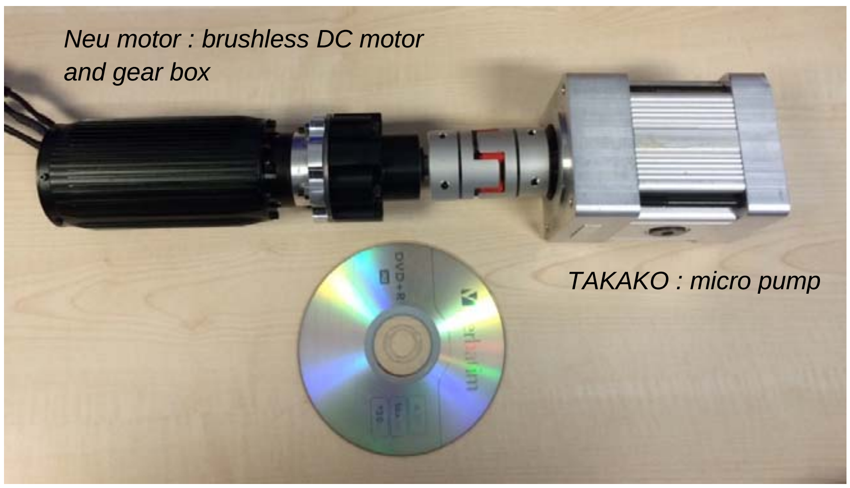


Figure 8. Picture of chosen pump and electric motor with a standard-size compact disc to indicate the size

3.4. Accumulator

To absorb sudden change of flow rate and deviation of flow rate because of pump, accumulator is required. In this case, diaphragm accumulator was chosen to compensate 3 L/min which is difference between maximum flow rate 13 L/min and average flow rate 10 L/min. To select appropriate accumulator we assume adiabatic change, actuation time of accumulator is 0.2s and minimum operation pressure is 18MPa. If we want to sustain 3L/min, the accumulator needs to provide 0.1 L. Pre-charged pressure 14.4MPa is calculated by using is recommended compression ratio 0.8. From these values required pre-charged nitrogen gas volume is by calculated below equation. Vi and Pi means the volume and the pressure of nitrogen gas of each state. i=0 is pre-charged state, i=1 is minimum hydraulic pressure state and i=2 is maximum hydraulic pressure state. Efficiency of accumulator η and is assumed 0.95.

$$V_0 = \frac{V_1 - V_2}{\left(\frac{P_0}{P_1}\right)^{\frac{1}{1.4}} - \left(\frac{P_0}{P_2}\right)^{\frac{1}{1.4}}} \times \frac{1}{\eta} = 0.17\,L \qquad (2)$$

We search accumulator which has gas volume more than 0.17 L and found HYDAC 0.32 L diaphragm accumulator as smallest and lightest one.

3.5. Filter and Oil cooler

The servo valves require NAS 3 or lower, which means contamination must be smaller than 3μm. We choose a line filter which is a lightweight filter among the one fulfill this requirement and its maximum operating pressure is 20 MPa. Estimated pressure drop is 0.15MPa at flow rate 13L/min, thus we considered this pressure drop is negligible. We choose the oil cooler which has aluminum honeycomb shape and its cooling capacity is estimated 2300W with 9.0m/s air flow. Since we use constant volumetric pump, if robot does not consume kinetic energy e.g. standing, most of energy will be turned into heat and it is difficult to cooling such amount of heat by the oil cooler and also a lot of heat dissipation decrease energy efficiency of the robot. In order to avoid these problems we will control the rotation speed of the pump depends on movement of the robot.

3.6. Reservoir

In case of walking robot whole body is always vibrating and the air can enter into the oil because of walking motion, although conventional reservoir is usually open to the atmosphere. In order to solve this problem some aircraft uses self-pressurizing reservoirs (boot strap reservoirs). However commercial self-pressurizing reservoir is too bulky for mobile robot, thus we uses an accumulator as a reservoir.

Maximum system oil difference was estimated 0.19 L (linear actuator x8 = 0.06L, accumulator = 0.1 L, temperature variation = 0.03L). By following same procedure with section 3.4, if we assume maximum pressure = 0.5MPa, minimum pressure =0.2MPa and pre-charged pressure = 0.17MPa, required gas volume is calculated as 0.47L. Since this accumulator is only used under low pressure.

3.7. Manifold

MiniHyQ has 12 active joints and its each actuator is control by the high performance servo valve (Moog E024). Two separate centralized manifolds are used for front and hind legs. Both manifolds are identical and each has capacity of six valves. A centralized manifold shown in Figure 9 that is placed in torso rather than using distributed manifolds on each leg and this design is validated by FEM analyses.

Fingure 9: MiniHyQ's centralized manifold

4. DISCUSSION & CONCLUSION

MiniHyQ is a pioneer, slightly smaller in size than HyQ [2] but the lightest among the existing hydraulically actuated quadruped robots [1][12][14]. The development of an on-board power pack for the MiniHyQ robot is a significant step forward in miniature hydraulics. We demonstrated the development of an on-board hydraulic system and thoroughly described how we designed on-board power pack for it.

Future work: Future experiments will be performed on MiniHyQ using an on-board power pack. The optimization of MiniHyQ's servo valves is also the part of future work.

ACKNOWLEDGMENTS

The authors would like to thank also the colleagues that collaborated for the success of this project: Michele Focchi, Jake Goldsmith, Bilal Ur Rehman, Ioannis Havoutis and our team of technicians. This research has been funded by the Fondazione IstitutoItaliano di Tecnologia.

REFERENCES

[1] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, and the Big- Dog Team. Bigdog, the rough-terrain quadruped robot. In IFAC, 2008.

[2] C. Semini, N. G. Tsagarakis, E. Guglielmino, M. Focchi, F. Cannella, and D. G. Caldwell, "Design of HyQ - a hydraulically and electrically actuated quadruped robot," IMechE Part I: J. of Systems and Control Engineering, vol. 225, no. 6, pp. 831–849, 2011.

[3] T. Boaventura, C. Semini, J. Buchli, M. Frigerio, M. Focchi & D G. Caldwell. 2012. Dynamic torque control of a hydraulic quadruped robot. In IEEE International Conference in Robotics and Automation, pp. 1889–1894, 2012.

[4] H. Khan, C. Semini, and D. G. Caldwell, "Actuator sizing for highly dynamic quadruped robots based on squat jumps and running trots," Int. Conf. on Climbing and Walking Robots (CLAWAR), Jul 2013.

[5] C. Semini, H. Khan, M. Frigerio, T. Boaventura, M. Focchi, J. Buchli, and D. G. Caldwell, "Design and scaling of versatile quadruped robots," in CLAWAR Conference, 2012.

[6] H. Khan, R. Featherstone, D. G. Caldwell, and C. Semini, "Bioinspired knee joint mechanism for a hydraulic quadruped robot," in International Conference on Automation, Robotics and Applications (ICARA), 2015.

[7] T. Boaventura, G. Medrano-Cerda, C. Semini, J. Buchli, and D. G.Caldwell, "Stability and performance of the compliance controller of the quadruped robot hyq," in IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 2013.

[8] V. Barasuol, J. Buchli, C. Semini, M. Frigerio, E. R. D. Pieri, and D. G. Caldwell, "A reactive controller framework for quadrupedal locomotion on challenging terrain," in IEEE International Conference on Robotics and Automation (ICRA), 2013.

[9] S. Schaal, "The SL simulation and real-time control software package." Technical Report, (Online) Accessed October 2014 at http://wwwclmc.usc.edu/publications/S/schaal-TRSL.pdf, 2006.

[10] B. T. Krupp, J. E. Pratt, "A power autonomous monopedal robot", Proc. of the International Society of Optical Engineering (SPIE), 2006

[11] S. Seok, A. Wang, M. Y. Chuah, D. Otten, J. Lang, and S. Kim, "Design principles for highly efficient quadrupeds and implementation on the MIT cheetah robot," 2013 IEEE International Conference on Robotics and Automation, May 2013.

[12] J. T. Kim, J. S. Cho, B.-Y. Park, S. Park, and Y. Lee, "Experimental investigation on the design of leg for a hydraulic actuated quadruped robot," in 44th International Symposium on Robotics (ISR), 2013.

[13] A. Winkler, I. Havoutis, S. Bazeille, J. Ortiz, M. F. Focchi, R. Dillmann, D. G. Caldwell, and C. Semini, "Path planning with force-based foothold adaptation and virtual model control for torque controlled quadruped robots," in IEEE International Conference in Robotics and Automation, 2014.

[14] F. Gao, C. Qi, Q. Sun, X. Chen, and X. Tian, “A quadruped robot with parallel mechanism legs,” in IEEE International Conference on Robotics & Automation (ICRA), 2014.

[15] T. Kim and S. Park, “A composite algorithm for flow rate and ground reaction force reduction in a hydraulic actuated quadruped robot with kinematic redundancy,” in IEEE International Conference on Mechatronics and Automation, 2014.

[16] H. Khan, S. Kitano, M. Frigerio, V. Barasuol, R. Featherstone, D. G. Caldwell, and C. Semini, "Development of the lightweight hydraulic quadruped robot -MiniHyQ". In The IEEE International Conference on Technologies for Practical Robot Applications (TePRA), 2015.