Mechanism design and flow estimation method of a hydraulic actuated robot

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Abstract

With the extension of robot applications, robot with high adaptability and high load capacity become a new focus in the recent years. Wheeled robots have the advantages of high load and speed, but this is limited in specified substrate. Legged robots inspired by the legged animals could move on rough terrain, so it was selected as a robot prototype for the high adaptability and high load capacity robot. In this paper, the structure of a hydraulic actuated quadruped robot was proposed. And then the kinematics of single leg was analysed. To estimate the required flow, a trot gait with 50% duty cycle is schemed and the trajectories of feet were planned. Then the total flow of the system required was calculated with the planned motion. The result can be taken as a reference to optimize the robot mechanism and select the hydraulic system.

Keywords: hydraulic actuated, quadruped robot, mechanism design, flow estimation

1 Introduction

The wheel is a remarkable invention as an important transportation in human history. Vehicles with wheels have the advantages in speed, efficiency and payload on flat road, but the application was greatly restricted due to the requirement of road [1], though it could be designed to achieve an arbitrarily small turning radius [2] or to negotiate extreme terrain [3] such as the planetary rover. Most of the terrain on earth is rough and irregular, and there are also many special circumstances that human cannot or difficult to achieve, such as the field of natural disasters and space exploration. So an effective and reliable mechanism is desired for search and rescue in the extreme environments. Moreover, legs offer an alternative for such application.

Legged mechanism is prior to the wheeled in terrain adaptability, obstacle negotiation and achievement of variable locomotion mode by using intermittent footholds [4]. Adopted by most of the animals on the terrain after millions of years' evolution, legged mechanism must have its natural superiority, and animals support excellent bionic prototypes for the design and control of robots. In the process of natural selection, Strong adaptability and effective motion rhythm mode of animals were established, which is available for the study of improve the performances of robots.

Quadruped robot needs the least feet for the static stability, and has the potential to realize variable motion type, such as trot, pace, jump and so on. Quadruped robot greatly developed in the past several decades. Many of the existing robots are actuated by motors, and some unconventional actuators are also used for the study. Piezoelectric material have been used in the designs of small motion mechanisms [5, 6]. Energy efficiency was mainly concerned on such functional material actuator, and more attentions were paid to the performance of the materials. With the extension of applications, robots, which have the performance of high power density, high motivation and high payload, is desired to help people to do dangerous and boring work in real life. Hydraulic actuator has the characters of high power density and high power-to-weight ratio. Hydraulic system has been adopted to be the actuator for robots [7].

Hydraulically actuated quadruped robots have become another research focus due to its distinctive character [7, 8]. LS3 (Legged Squad Support Systems, LS3) is a large, dynamic quadruped, produced by Boston Dynamics. It is by far the most impressive robot designed to go anywhere Marines and Soldiers go on foot, helping carry their load. As the previous product of LS3, BigDog is their another amazing product [9, 10]. They are highly dynamic and have demonstrated recovery ability from significant perturbations, including being kicked or unexpectedly slipping on ice, using deliberate foot placement to control body attitude, although most of the details on their design and control remains unpublished. HyQ is another hydraulically actuated quadruped robot developed by Italy researchers [11, 12]. It was reported on the cyber

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that HyQ has robust motion on the treadmill with desultory wood block on the surface.

2 Mechanism design of robot

The objective of this project is to develop a robot that can walk, trot and jump over rough terrain. The robot can balance dynamically and recover balance from unexpected disturbances such as rough terrain or external forces acting on robot. The weight is about 70kg including power and control system, and the payload capability is 50kg. The designed velocity is about 1m/s.

2.1 OVERVIEW OF THE ROBOT

Legs of robot are driven by hydraulic cylinders and controlled by servo valves. Motor and pump are needed as the power system to actuate the cylinders. The robot would be capable of highly dynamic locomotion as hydraulic actuation allows the handling of large payloads and impact forces, high bandwidth control, high power-to-weight ratio and superior robustness.

The CAD model rendering of the robot with a description of key parts and components is shown in Figure 1.

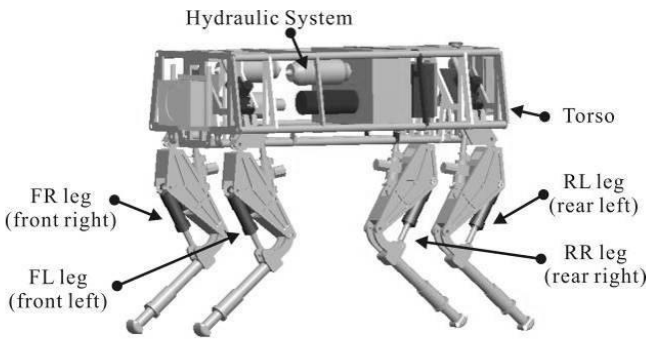


FIGURE 1 CAD model of hydraulically actuated robot

It is built up of a robot torso and four identical legs generally. Four legs are arranged on the torso symmetrically in the forward/backward configuration, where the front and hind knees point to each other. The torso is around 1.05m long and 0.56m wide to satisfy the space requirement of motion range of each leg and all the power support components. The total weight of robot including power system is about 72kg. Single leg excluding the parts embedded in the torso (the cylinder that controls the abduction/adduction of leg and the corresponding hip joint) is around 5.97kg.

The material of all mechanisms of robot is hard aluminium alloy, which have low density and high hardness. The torso is composed of aluminium tube and sheet metal. Moreover, the structure of leg mechanism is hollow. Leg and torso mechanisms are analysed by Finite Element Analysis software to determine the minimum thickness of tube and sheet metal that provide enough force and torsion.

2.2 LEG DESIGN

Three active revolution degrees of freedom (DoFs) are assigned to each leg to satisfy the requirement of Omni bearing motion ability. One controls the abduction and adduction of leg, and the others two control the flexion and extension. Three hydraulic cylinders are used to actuate the joints, which is the least requirement to allow a foot positioning in the three dimensional workspace round the hip. Leg mechanism is shown in Figure 2.

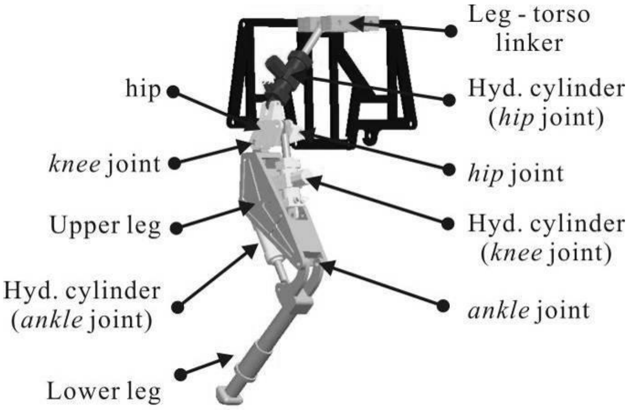


FIGURE 2 Mechanism of single leg.

Leg abducts or adducts around the hip joint axis parallel to the longitudinal axis of the body, responsible for the lateral motion of leg. Knee joint, located between hip and upper leg, is responsible for the upper leg motion that brings the knee closer/further from the torso. Ankle joint, located between upper and lower leg, is responsible for motion of lower leg that brings the foot upper/lower from the ground. Knee joint and ankle joint control the leg segments by flexion and extension along the rotation axis, and the axes of the two joint axes are parallel.

3 Kinematic analysis of single leg

The rotation joint of leg is actuated by the revolution of each hydraulic cylinder. Therefore, the relationship between the position of foot in workspace and the displacements of cylinders is necessary for the motion control of legs, which is also used for the further flow estimation.

According to the modified D-H method, the motion coordinate frame of single leg is built as shown in Figure.3. Take J1, J2 and J3 represent the hip, knee and ankle joints respectively. Σ1 is built on the cross point of the axis of J1 and the common perpendicular line between axes of J1 and J2. In addition, the base coordinate system, fixed on the hip joint, is coincident with Σ1 initially. Σ2 and Σ3 are placed on the rotation joints J2 and J3. Σ4 is placed at the centre of foot. Moreover, the specific position and orientation of each coordinate system are shown in Figure 3. Symbols c1, c2 and c3 represent the rotation angles of Z axis, and the arrows show the positive direction.

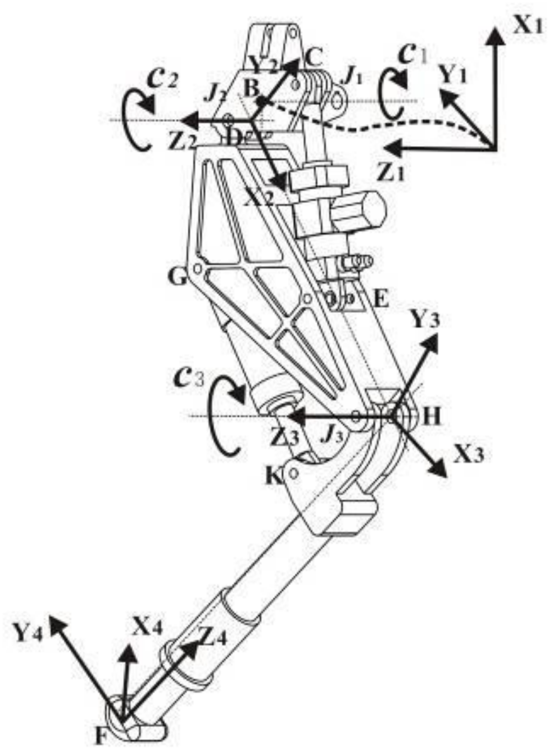


FIGURE 3 Kinematics coordinates frames.

The transform matrix between coordinates could be obtained according to Craig's convention. So the homogeneous transform matrix from the base coordinates to the foot coordinates could be deduced.

According to the geometrical relation, the displacement of cylinder and joint angle could be represented as follow,

$$l_i(t) = f(c_i(t)), \tag{1}$$

where, f is the function between displacements of cylinder and joint angle. l and c are the displacements of cylinder and joint angle. i (i = 1, 2, 3) is the hip, knee and ankle joint, respectively.

Assumed that the p_x, p_y, p_z are the displacements of foot along axis direction in the base coordinate system. The relation between joint angles and foot displacements, represents as f could be deduced based on the kinematical analysis,

$$c_i(t) = g(p_x(t), p_y(t), p_z(t)). \tag{2}$$

So the displacements of each cylinder could be presented as the composite function of the foot displacement based on (1) and (2):

$$l_i(t) = f(g(p_x(t), p_y(t), p_z(t))). \tag{3}$$

The speed of cylinder can be deduced from (3),

$$\frac{dl_i}{dt} = \frac{\partial l_i}{\partial c_i}\left(\frac{\partial c_i}{\partial p_x}\frac{dp_x}{dt} + \frac{\partial c_i}{\partial p_y}\frac{dp_y}{dt} + \frac{\partial c_i}{\partial p_z}\frac{dp_z}{dt}\right), \tag{4}$$

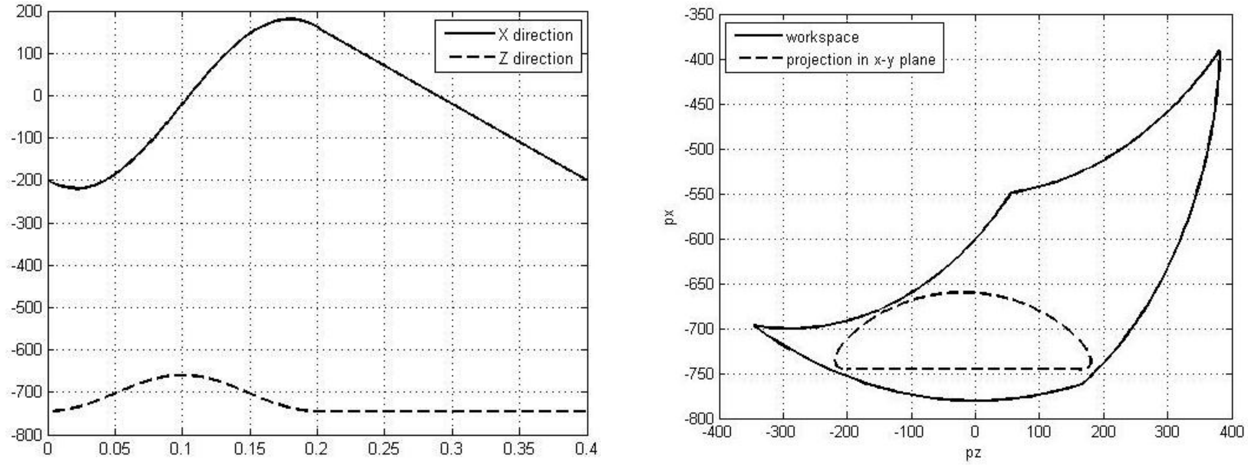
Based on (4), the speed of each cylinder can be calculated if the trajectory of foot is given.

4 Trajectory plan of foot

The flow of hydraulic system is estimated when trotting in the air with the longest stride length in the workspace to obtained the minimum flow. The trajectories of robot foot are planned assumed that robot moves at constant speed without waggling at lateral and vertical directions. The trajectory along each direction is planned as below:

$$p_z(t) = \begin{cases} 45000*(t - \frac{T}{20})^2 - 218 & 0 \le t \le \frac{T}{20} \\ -20 - 200*\cos(0.4\pi T*(t - \frac{T}{20})) & \frac{T}{20} < t \le \frac{T}{2.5} \\ -4500*(t - 0.45T)^2 + 180 & \frac{T}{2.5} < t \le \frac{T}{2} \\ 160 - 1800*(t - \frac{T}{2}) & \frac{T}{2} < t \le T \end{cases}$$
$$p_x(t) = \begin{cases} -702.5 - 42.5*\cos(0.25\pi T) & 0 < t \le \frac{T}{2} \\ -745 & \frac{T}{2} < t \le T \end{cases} \tag{5}$$
$$p_y(t) = 0 \qquad 0 \le t \le T$$

The trajectory of foot was planned relative to the hip joint. On swing phase (0 - 0.5T, T=0.4s) two quadratic functions and one trigonometric function were adopted to compose the trajectory along the moving direction (Z direction), and one trigonometric function was used along the up-down direction (X direction). On stance phase, foot moved at a constant speed along moving direction and kept the constant height at up-down direction. Shown in Figure 4 are the trajectories of front left foot. Feet could move with smooth velocity and acceleration based on the planned trajectory. In Figure 4, the step height is 85mm; step length of single leg is 400mm, the velocity is 1m/s.



a) b)

FIGURE 4 Planned trajectory of front left foot: a) is the trajectories at moving direction and up-down direction; b) is the project of workspace and trajectory in X-Z plane.

5 Flow estimation of hydraulic system

Estimated oil flow is an important parameter for the design of hydraulic system as it directly affects the size of the on-board pump, tank, cooler and pump engine, and therefore the total robot mass.

For an approximate analysis of the system, the leakage flow in the valve and cylinder and the compressibility flow in the lines and volumes can be neglected. The flow Q_{hdu} inside a hydraulic drive unit that consists of one cylinder can be expressed as follows:

$$Q_{hdu} = \begin{cases} v_{cyl}\dfrac{\pi D^2}{4\eta_v} & \text{if } v_{cyl} > 0 \\ \left|v_{cyl}\right|\dfrac{\pi (D^2 - d^2)}{4\eta_v} & \text{if } v_{vcl1} < 0 \end{cases}, \quad (6)$$

where, v_{cyl} is the velocity of cylinder rod which equals to dl_i/dt. D is the diameter of cylinder barrel. And d is the diameter of cylinder rod. η_v is the volumetric efficiency, normally the value is 1.

The selected hydraulic is dissymmetrical. Oil flows into the cylinder barrel from the side without rod when $v_{cyl} > 0$, and from the other side with rod when $v_{cyl} < 0$.

For the estimation, it assumed that the hydraulic cylinder actuating the hip joint was fixed and the robot could move steady. So the total oil flow curve can be obtained by adding all the 8 cylinders at the same time ticks. The curve in one cycle is shown in Figure 5. And the peak value of flow in about 76.4L/min.

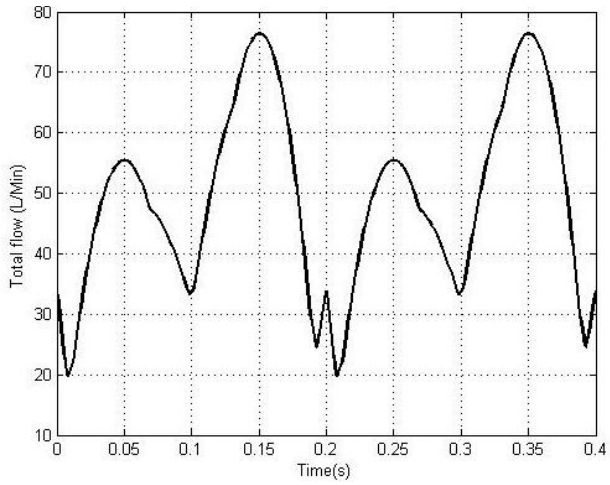


FIGURE 5 Total oil flow of robot in one cycle

6 Conclusions and discussion

The largest total oil flow is mainly decided by the absolute speed of all the motion cylinders at the same time if the cylinders are selected. Shown in Figure 6 are the speed curves of all the six motion cylinders.

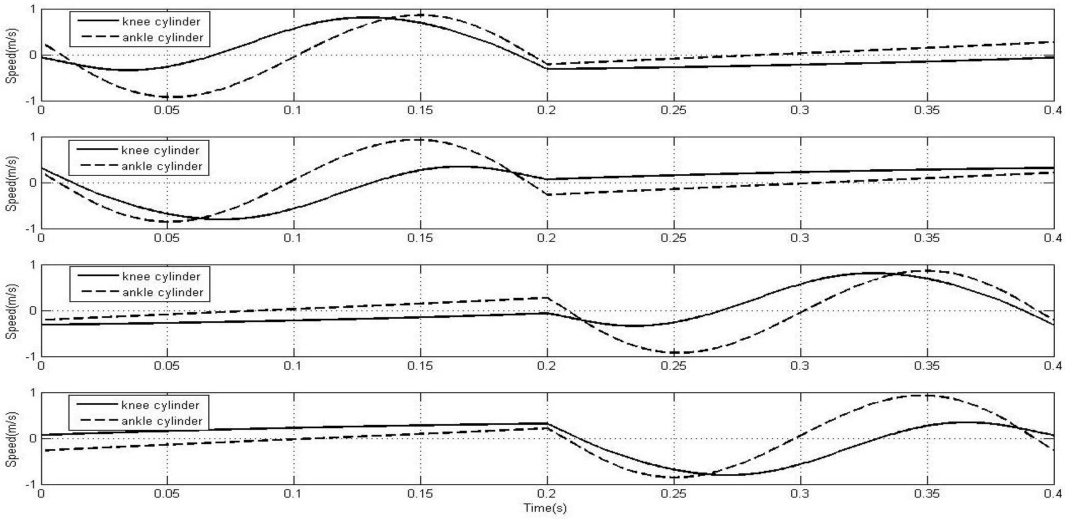


FIGURE 6 The speed curves of motion cylinders. The solid lines are the speeds of each knee cylinder, and the dashed are the speed of ankle cylinder.

Compared to cylinders speed curves with the total oil flow it could be found that the maximum value of flow is at 0.15s and 0.35s, which is corresponding with the time that the maximum sum of absolute cylinders speed. Therefore, the total flow will increase with the increase of cylinders speed. Moreover, the flow will increase if the motion speed robot increases by increase the step frequency. The total load of robot is improved at the cost of increase the total flow by keeping the cross points between cylinder and the relative leg.

In this paper, a hydraulic actuated quadruped robot prototype is designed. The method of estimating the total oil flow was deduced. At last, the oil flow was calculated, which offered a reference to the design of power system.

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References

[1] Michael L 1983 *Am Nat NLM* **121**(3) 395-408
[2] Brett B, Jeremy S, Rybski P E, Veloso M 2005 *Ind Rob* **32**(2) 149-56
[3] Karl I, Steven D 2004 *Int J Rob Res* **23**(10-11) 1029-40
[4] Marc H R 1986 *Commun ACM* **29**(6) 499-514
[5] Taesin H and Chong-Ho C 2007 *Rob Auton Syst*. **55** 795-810
[6] Seok H, Tedy W, Hoon C P, Nam S G 2007 *J Bionic Eng* **4**(3) 151-58
[7] Xuewen R, Yibin L, Jiuhong R, Bin L 2012 *J Mech SCI Technol* **26**(4) 1171-7
[8] Cai R B, Chen Y Z, Lang L, Wang J, Ma H X 2013 *Int J Adv Robot Syst* **10**(26) 1-8
[9] Raibert M, Blankespoor K, Nelson G, Playter R 2008 *Proc. of the 17th World Congress the International Federation of Automatic Control* Seoul Korea 10822-25
[10] Buehler M, Playter, R, Raibert M 2005 *Int Symp on Adaptive Motion of Animals and Machines* Ilmenau Germany 526
[11] Boaventura T, Focchi M, Frigerio M, Buchli J, Semini C, Medrano-Cerda G A, Caldwell D G 2012 *IEEE Int. Conf on Intelligent Robots and Systems 2012 October 7-12* Vilamoura Algarve Portugal, 4066 -71
[12] Shuang P, David T B, Emanuele G, Thiago B, Darwin G C 2012 *Proc of the 11th Biennial Conf. on Engineering Systems Design and Analysis 2012 July 2–4* Nantes, France 227-34

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