Review of Quadruped Robots for Dynamic Locomotion

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Abstract—This review introduces quadruped robots: MIT Cheetah [1], HyQ [2], ANYmal [3], BigDog [4] and their mechanical structure, actuation, and control.

I. INTRODUCTION
Quadruped robots are more and more popular in industry and academia recently.

II. ACTUATION AND STRUCTURE

A. Actuation
Classify by actuation, there are three different types of quadruped robots for dynamic locomotion: hydraulic, electric and hybrid.

1) Hydraulic Actuation: Hydraulic actuators are used in Big Dog [4], HyQ [2]. It provide many advantage [3]:

- Extremely high power.
- Extremely high force density.
- High resolution force estimation by load cells.
- High performance force control.

Thanks to these features, robots are robust against impulsive loads naturally. But the hydraulic actuation also has negative side [5] [3]:

- The hydraulic system is very complex.
- Energetically inefficient.
- Expensive.
- High inertial.
- High noise.

Fig. 3. Components of BigDog 2008 [Boston Dynamics Corp., 2008].
B. Electric Actuation

Compared with hydraulic actuation, electric actuation is more widely used in the quadruped robots in recent years.

1) Quasi Direct Driven: As we all know, high gear ratio reducer brings hard to model friction and un-backdriveable for actuators. The principal of QDD is low gear ratio (small than 1:10) with a low KV BLDC motor [6] [7] [8]. As a result, motor current control, which can be done at very high bandwidth, is equivalent to the regulation of the output force [3]. Figure 4 shows a QDD actuator used on MIT Mini Cheetah.

![Figure 4. Cross-sectional views of the actuator. On the left, bearings are highlighted in red, rotor in blue, and planet carrier in green [7].](image)

2) Series Elastic Actuator: Limited to high reduction ratio harmonic reducer, SEA can’t estimate torque sensorless and series elasticity give back many quantities that are lost when high reduction ratio reducer are introduced: a series elasticity with two encoders are installed for torque estimate. Feature more, humanoid Valkyrie [9] or the quadruped StarlETH [10] show the elasticity can store energy for energy-saving and prevent reducer damaging when robot having dynamic actuation. But the SEA has a lower dynamic response than other actuation cause by series elasticity. Figure 5 shows a SEA used in HyQ.

![Figure 5. Block Diagram of Series-Elastic Actuator [11].](image)

3) Joint:
   a) Full Rotation Joint: Bring more workspace, flexibility and different configurations to the quadruped. Figure 6 shows MIT Mini Cheetah’s leg with the modular actuators, which has changeable parameters. Optimize design parameters lead to a knee joint design that can perform a wide range of motion and optimized joint torque curve.

   ![Figure 6. Different configurations of ANYmal [3].](image)

   b) Isogram Mechanism [12]: Hydraulic quadruped also has much excellent mechanical design. HyQ has a bio-inspired knee joint mechanism for a linear hydraulic cylinder. This mechanism is based on the crossed four-bar linkage, which has changeable parameters. Optimize design parameters lead to a knee joint design that can perform a wide range of motion and optimized joint torque curve.

   ![Figure 7. The isogram mechanism [12].](image)

C. Leg design

1) Degree of Freedom: Most of the quadruped robots have 3 DoF each leg, which call "abad", "hip", "knee". Because 3 DoF can is the minimum DoF present 3 DoF ground reaction force which is suitable for force control in locomotion. Figure 8 shows MIT Mini Cheetah’s leg with the modular actuators.
2) Low Inertia: Both MIT Cheetah and ANYmal emphasize small inertia of leg which arrowed simplify the dynamics model of the robot when planning to control and also bring the high performance of leg when tracking the trajectory. As Figure 9 and Figure 8 show, all the actuator are mounted on the shoulder, the knee joint is driven by belt or linkage. The result is the CoM of the whole leg is quite near the adab/hip joint. Thanks to the position of CoM, the inertia of the leg is much lower than the robot body.

III. CONTROL

A. Actuator

1) Electric Motor: All BLDC is controlled by FOC (Field Oriented Control) for current/torque control at a very high frequency on the microcontroller. See [14] for a detailed discussion of FOC. In brief, use DQ0 (direct-quadrature-zero) to transform a 3-phase stator current to a single rotating reference frame. The motors behavior is roughly linear in the rotor reference frame, so high bandwidth current control can be easily achieved using discrete-time linear control techniques (like PI controller). Then transform Voltages from the rotor frame to the stationary stator reference frame by the inverse DQ0 transform.

2) Hydraulic Actuator: The Hydraulic system is so complex that we don’t discuss it here.

B. Locomotion

There are many dynamic locomotion algorithms like SLIP (Spring-Loaded Inverse Pendulum), MPC (Model Predictive Control), CPG (Central Pattern Generators), DRL (Deep Reinforcement Learning). We are going to introduce SLIP and MCP.

1) SLIP:

   a) Template and Anchor: It is also an important bioinspire method.

   b) SLIP Template: The SLIP [16] or Raibert Hopper is first used in dynamic locomotion by Marc Raibert in 1986. The SLIP like control algorithm is widely used in legged robots. The main idea is to take a big step forward during the fight when you want to decelerate, take a little step forward during the fight when you want to accelerate. Where $x_f$ is the forward displacement of the foot with respect to the center of mass, $T_s$ is the duration of the stance phase

   \[ \dot{x} = \frac{\dot{x} T_s}{2} + k_x (\dot{x} - \dot{x}_{ref}) \]  \(1\)

   \[ \Phi = \Theta - \arcsin\left(\frac{x_f}{r}\right) \]  \(2\)

   Control body attitude during stance (close loop by servo motor):

   \[ \Theta = 0 \]  \(3\)
Using SLIP to Biped and Quadruped: Raibert proposes the Virtual Legs theory which can implement SLIP on biped and quadruped [16]. In brief, the legs can be seen as a virtual leg when they meet the following properties:

- Synchronization
- Force Equation

BigDog: The virtual leg is used in BigDog, as Figure 16 shows, BigDog is running the algorithm base on the virtual leg. It adds the gait generator for different speed, foot trajectory planning to avoid collision and a state estimator. With the powerful actuators, BigDog can cross the rough terrain and balance under disturbance very well.

2) MPC: MPC is used in MIT Cheetah 3 and MIT Mini Cheetah.

The control system is consist of three part:

- Higher-level planning(green).
- Leg and body control(red).
- State estimations (blue).

Each leg has two controller switch in different mode:

a) Swing Leg Control: Use Raibert [16] method to calculate the foot placement, then generate the bezier curve for foot, use the impedance controller to follow the trajectory.

b) Ground Force Control: Ignore leg inertial, Ground reaction force is simply opposite of foot force. The control
The law used to compute joint torques for leg i is:

$$\tau_i = J_i^T R_i^T f_i$$  \hspace{1cm} (4)

where $f_i$ is the ground reaction force.

c) **Ground Reaction Force:** The most important point of whole locomotion is compute the ground reaction force which drive robot to desired CoM state. Convex-MPC compute the GRF by:

0. Modeling the quadruped according to rigid body dynamics.
1. Linearize the model
2. Reformulate MPC problem into QP (Quadratic Programming) problem
3. Solve the problem and exploring the calculated GRF as a ground force control desired.

Convert model from continuous to discrete time:

$$x(k+1) = \hat{A}x_k + \hat{B}u_k$$  \hspace{1cm} (9)

Write as a MPC problem:

$$\min_{u, x} \sum_{i=1}^{N} l(x(i), u(i))$$

s.t.

$$x_{(k+i)} = \hat{A}x(k+i) + \hat{B}u(k+i),$$

$$i = 0, 1, \ldots, N-1,$$

$$|u(k+i)| \leq u_{max},$$

$$i = 0, 1, \ldots, N-1,$$

$$|x(k+i)| \leq x_{max},$$

$$i = 1, 2, \ldots, N.$$  \hspace{1cm} (13)

Reformulate to a QP problem:

$$\min_u \frac{1}{2} U^T H U + U^T g$$

s.t.  \hspace{0.5cm} I \leq C U \leq u$$  \hspace{1cm} (15)

The controller works well in reality. It is worth mentioning that the controller does not require high accuracy of the model parameters, the robot can climb stairs [1] use the same controller and parameters although the pitch and roll angle not close to 0. The controller also works on a Mini Cheetah like a robot made by the author in which the motor and body are 15% heavier than the original.
C. Compute System

Recently, reduced use of microcontrollers, try to put more calculations on a small computer instead of a microcontroller is a trend. Most of quadruped use microcontroller only for FOC motor control, and other algorithms like implement, MPC are running on embedded Linux computer like NUC or UP board.

1) ROS: Figure 21 shows ANYmal’s locomotion PC and other PC for the high-level algorithm, the data is transferred over the network by the Robot Operating System (ROS) running on a low-latency patched Ubuntu, and the motor control command sent by CAN bus. This kind of architecture provides an efficient development and debugging.

2) RTOS: Most of the quadruped use Ubuntu which is a common desktop system for computation, but locomotion requires low latency and all tasks must be completed within a determinate time, in other words, a real-time operating system or even hard real-time operating system. We can make Ubuntu real-time by patch.

Figure 22 is the latency plot of 4.4 Linux kernel running on UP board with high stress. It shows that the RT PREEMPT patch can reduce the latency effectively and also stable the latency.

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