Scaling of Versatile Quadruped Robots for Running Trot

Hamza Khan, Claudio Semini and Darwin G. Caldwell
Department of Advanced Robotics, Istituto Italiano di Tecnologia, Genova, Italy.
{*hamza.khan, claudio.semini, darwin.caldwell*}@*iit.it*

1 Introduction

Legged robots have become a much more prominent field of robotics in recent years, due to their potential versatility and capability of performing tasks which conventional vehicles are unable to do. Most of the recent legged robots, however, lack the versatility of performing both precise navigation over rough terrain and the strong, fast motions that are necessary for dynamic tasks such as jumping and running. Presently very few examples exist besides BigDog [8] by Boston Dynamics and HyQ [11] by IIT.

To design such kind of machines, firstly the designer has to define the tasks that the robot should accomplish to then choose the actuator that satisfies the task requirements in terms of joint velocity and torque. It is easier for a designer to narrow down the desired dimensions and mass of the robot. But when it comes to the selection of actuators, it is challenging to figure out the appropriate joint velocity and torque limits. The aim of this work is to build a scaling tool that helps the quadruped robot designers to select actuators that fulfill the desired requirements. We started our study using the squat jump as a characteristic motion for highly dynamic robots, obtaining peak values of joint velocity and torque in relation to robot mass, size and desired jump height [10]. This paper presents the extension of that study to a running trot to get peak hip and knee joint torques and velocities in relation to forward velocity, robot mass and leg segment length.

2 State of the art

Biological studies have shown that all legged animals typically run with similar center of mass (CoM) motions relative to the (approximately) horizontal ground [13]. Blickhan and Full showed in one of their studies that the running motion for multilegged locomotion behaves like a bouncing monopod and they calculated the compression of a virtual monopod's leg and its stiffness from the animals' mechanical-energy fluctuation and ground-reaction force [2]. A CoM trajectory of the legged robot during a running trot can be modeled by simple models (e.g. SLIP) [1] and more accurate models (e.g. M-SLIP) [6]. A spring-loaded inverted pendulum (SLIP) model is a simple way to model the CoM trajectories of legged locomotion during running. It offers a small stability domain on the steps-to-fall map. But its stability domain for running motion can be enhanced by swing-leg retraction [12] and it also reduces the foot speed which helps to reduce impact energy losses, minimize foot slippage and decrease peak forces. But in this work the simple SLIP model is used and it is sufficient to get peak forces in stance phase. One of the aims of this work is to get upper boundaries of joint torque and velocity for a given forward velocity.

Some similar studies were conducted for the electric DC motor sizing of a bounding robot [3] and hopping monopod robot [4]. But these studies were limited to quadruped robots with telescopic legs or a specific type of actuator. The current work is for quadruped robots with articulated legs and it is not restricted to only one type of actuators.

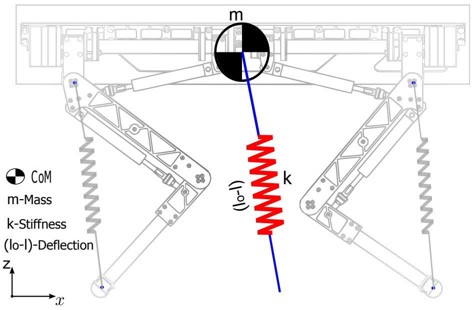

Figure 1: The equivalent virtual spring (connected to CoM) represents the virtual linear spring of a diagonal pair of legs

3 Running Trot Simulation

Desired joint torques are generated by placing a virtual linear spring between the hip and foot of each articulated robot leg [7] to control the motion of the leg. Each virtual spring of a diagonal leg pair is working synchronously in a trot and can be represented by one equivalent virtual spring, Fig. 1. The CoM motion of any quadruped during a running trot can be approximated by the SLIP model as it is observed in animals. A point mass m that is attached to a mass-less linear spring can be described as a SLIP model where k is the spring stiffness and l_0 is the rest length. During stance phase, the spring force exerted on the ground is defined as $k(l_0 - l)$. During flight phase, the mass follows a parabolic trajectory under the law of Gravitation. We define the spring rest length in relation to the leg segment length l_{ls} of each articulated robot leg as follows: l_0=$K_l l_{ls}$, where K_l is ratio between the leg segment length and the spring rest length. In our simulation K_l is equal to 1.41, which we assume to be a good value based on our experience with HyQ. From the SLIP model, we know the foot trajectory in Cartesian coordinates of the equivalent virtual spring leg during stance. Using the leg Jacobian, we can calculate the angular position, velocity and acceleration of hip and knee joints of the articulated robot leg. The ground reaction forces (GRF) in stance phase depend on the virtual leg deflection and its stiffness. In our simulation it is assumed that the robot mass is evenly distributed and that the robot torso is always parallel to the ground. During the stance phase of a running trot only two feet of a quadruped touch the ground. So the GRF for each articulated robot leg can be defined as $F = F_{vl}/2$ assuming evenly distributed load, where F_{vl} is the GRF for the equivalent virtual spring.

The leg's GRF is then transformed into hip and knee joint torques with the Jacobian transpose. During running humans and animals adjust their leg stiffness according to the ground stiffness [5]. In this work ground stiffness is assumed constant and the equivalent virtual spring stiffness and angle of attack is chosen from the stability domain of steps-to-fall map of the SLIP model.

4 Simulation and Experimental Results

Based on the SLIP model we performed a number of simulations for a range of forward velocities and leg segment lengths. First of all, suitable SLIP parameters (spring stiffness and angle of attack) had to be calculated for each input pair based on the steps-to-fall map. The SLIP parameters with the lowest spring stiffness that resulted in stable hopping of 50 or more steps were then selected. This way low impact peaks were obtained. Fig. 2 shows the peak joint torque scaled by the robot's body weight (BW) for different leg segment lengths and forward velocities. White areas indicate where the SLIP model failed to perform 50 steps for the given parameter range. For the validation of our selected approach we used HyQ's leg segment length (0.35m) and robot mass (73kg) and tuned the SLIP parameters until we obtained a matching hopping frequency with experimental results of a running trot that was performed on a treadmill at a slow speed [9]. The matching parameters are 59° and 16 kN/m, which resulted in a forward velocity of 3m/s. Fig. 3 on the top shows the vertical position of the SLIP model's CoM. Fig. 3 center and bottom plots show the GRF of the front and hind leg of each diagonal leg pair, showing both simulation and experimental results. As can be seen in these plots, the model used in this work is sufficient to predict approximate vertical GRF.

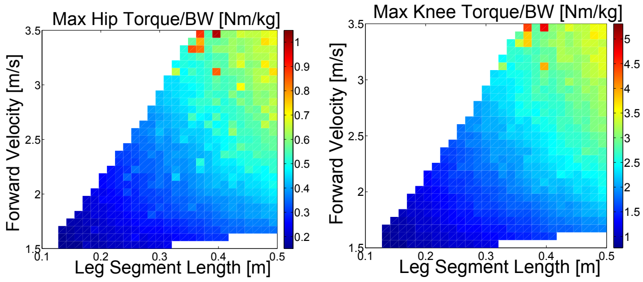

Figure 2: *Left*: plot of maximum hip joint torque scaled by the robot's body weight (BW) for different leg segment lengths and forward velocities. *Right*: plot of maximum knee joint torque for different leg segment lengths and forward velocities.

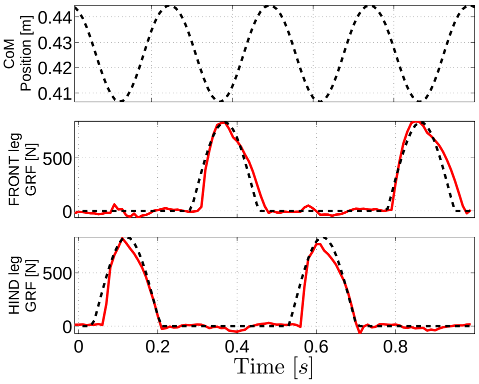

Figure 3: *Top*: Simulation of Vertical position of CoM (black dashed). *Center*: Front leg GRF experimental (red solid) and simulation (black dashed). *Bottom*: Hind leg GRF.

5 Open Questions

How to select appropriate actuators to design a versatile and highly-dynamic quadruped robot? How to evaluate if the desired performance lies inside the robot actuator limits without the need to implement stable running controllers? How to obtain required joint range of motions?

References

[1] R. Blickhan. The spring-mass model for running and hopping. *Journal of Biomechanics*, 22:1217–1227, 1989.

[2] R. Blickhan and R.J. Full. Similarity in multilegged locomotion: bouncing like a monopode. *Journal of Comparative Physiology*, 173:509–517, 1993.

[3] P. Chatzakos and V. Papadopoulos. The influence of dc electric drives on sizing quadruped robots. In *IEEE ICRA Conference*, 2008.

[4] P. Gregorio, M. Ahmadi, and M. Buehler. Design, control, and energetics of an electrically actuated legged robot. *IEEE Transactions on Systems Man and Cybernetics*, 27:626–634, 1997.

[5] H. Hobara, E. Kato, Y. Kobayashi, and T. Ogata. Sex differences in relationship between passive ankle stiffness and leg stiffness during hopping. *Journal of Biomechanics*, 45:2750–2754, 2012.

[6] F. Peuker, A. Seyfarth, and S. Grimmer. Inheritance of slip running stability to a single-legged and bipedal model with leg mass and damping. In *BioRob*, pages 395 –400, june 2012.

[7] J. Pratt, C.M. Chew, A. Torres, P. Dilworth, and G. Pratt. Virtual model control: An intuitive approach for bipedal locomotion. *The International Journal of Robotics Research*, 20(2):129–143, 2001.

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

[9] C. Semini, J. Buchli, M. Frigerio, T. Boaventura, M. Focchi, E. Guglielmino, F. Cannella, N. G. Tsagarakis, and D. G. Caldwell. HyQ – a dynamic locomotion research platform. In *Int.l Workshop on Bio-Inspired Robots*, 2011.

[10] C Semini, H Khan, M. Frigerio, T. Boaventura, M. Focchi, J. Buchli, and D. G. Caldwell. Design and scaling of versatile quadruped robots. In *Int. Conf. on Climbing and Walking Robots (CLAWAR)*, 2012.

[11] 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*, 225(6):831–849, 2011.

[12] A. Seyfarth, H. Geyer, and H Herr. Swing-leg retraction: a simple control model for stable running. *The Journal of Experimental Biology*, 206:2547–2555, 2003.

[13] M. Srinivasan and P. Holmes. How well can spring-mass-like telescoping leg models fit multi-pedal sagittal-plane locomotion data? *Journal of Theoretical Biology*, 255:1–7, 2008.