On Trajectory Generation and Active Impedance for Running Trotting

Victor Barasuol, Jonas Buchli*, Victor J. De Negri**, Edson R. De Pieri***,
Darwin G. Caldwell and Claudio Semini
Advanced Robotics, Istituto Italiano di Tecnologia, via Morego, 30, 16163 Genova / victor.barasuol@iit.it
*Agile & Dexterous Robotics Lab, ETH Zurich, Zurich, Switzerland
**Dept. of Mechanical Engineering / ***Dept. of Automation and Systems, UFSC, Florianópolis, Brazil

1 Introduction

Legged robots have the potential to perform highly dynamic locomotion both on flat and uneven terrain. However, finding suitable joint references and feed-forward actions that make quadrupedal locomotion robust to sudden disturbances has proved to be a challenge. Since the bandwidth of the controllers limits the accuracy of any form of desired reaction, proper trajectory generation, based on the robot hardware limitations, becomes an important task. In addition to proper trajectory generation, another important requirement for fast maneuvers (such as acceleration, deceleration and heading at higher speeds) is to have legs whose impedance can be adjusted as the requirements changes. To achieve such rapid adjustments, robot joints must be torque controlled.

In this work we present our first experimental results on more dynamic gaits and a discussion about the importance of the shape of the swing leg trajectory to the locomotion robustness. We focus on generating a running trot pattern for the fully torque controlled hydraulically actuated quadruped HyQ [1]. The running trot is a symmetrical gait in which diagonal legs swing in unison. The difference between a running trot and the walking trot is the occurrence of a "flight phase" in the running trot (a ballistic phase in which there are no legs in ground contact).

Here we explore the use of the Reactive Controller Framework (RCF) proposed in [3] to achieve more dynamic locomotion, e.g., a forward velocity of approximately 3 m/s and step frequencies around 2.5 Hz for a 80 kg robot. In the following approach we enforce the gait periodicity by means of trajectory generation and adjust the legs impedance to match a proper resonant motion, during the leg stance phase. We also present a discussion about how the shape of the swing leg trajectory may affect the running, and may provide robustness against an non-optimal selection of impedance, external disturbances and trajectory tracking errors.

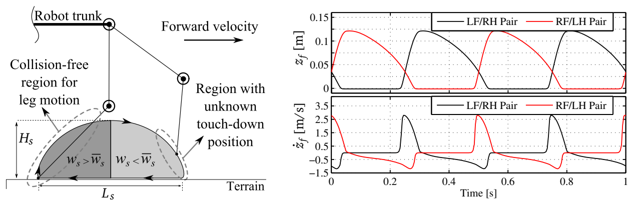
Recent research has presented algorithms based on gait optimization in order to improve quadrupedal locomotion [4], [5]. However, an analysis that focus on how the leg swing trajectory affects the performance of dynamic gait patterns, as the running trot, is still missing. While we described the kinematic references used for running trots in [2], this abstract discusses for the first time their benefits.

2 Methodology - Motion Generation and Control

In a running trot the flight phase depends on the ratio between the time that a leg stays in contact with the ground (the *stance phase*) and the time that a leg takes to swing to the next foothold (the *swing phase*). This ratio is called the *Duty Factor*, D_f, and varies between 0 and 1.

The RCF trajectory generator is inspired by the Central Pattern Generator (CPG) approach. It generates a modulated semi-elliptic foot trajectory, for each leg, parametrized according to the leg step length L_s and step height H_s. Each foot trajectory has an instantaneous angular frequency w_s, which is associated with the corresponding leg step frequency f_s. Figure 1(a) illustrates the generated foot trajectory.

For a running trot we explore the independent parameter modulation capability of the RCF approach to generate a variable swing velocity of the leg. The idea is to move the leg faster in regions where there is a low risk of impact with obstacles, while slowing it down as it approaches a touchdown region, thereby reducing the impact forces. Figure 1(b) illustrates the generated vertical foot displacement and velocity.



(a) (b)

Figure 1: Modulation of the angular frequency w_s during leg swing phase. **(a)** Modulation regions according to swing leg position. $\bar{w}_s$ stands for the average angular frequency $\bar{w}_s$ during swing phase. **(b)** The plot shows the foot's relative position z_f (step height) and the corresponding velocity $\dot{z}_f$ references for each pair of diagonal legs (Left-Front/Right-Hind and Right-Front/Left-Hind legs).

The ratio between the swing period in the collision-free region and the swing period in the unknown touch-down region is defined as K_v. The greater K_v the slower the foot approaches the ground.

To track the desired references the joint controller block (see [3]) generates a control action designed to emulate a spring loaded telescopic leg. This may be considered to be a virtual spring-damper system connected between each hip joint and its respective foot. This creates a more symmetric behaviour in terms of ground reaction forces during the stance phase.

The running trot is stabilized by a trunk controller and a push recovery block (see [3]). The trunk controller receives all the information about the desired motion and posture and tries to track them by applying forces and moments on the trunk. The push recovery block receives information only about the trunk motion and generates foot holds deviations to reduce motion errors. The trunk controller also applies push forces against the ground for the maintenance of the body flight phase. It is important to mention that gravity effects are also compensated.

3 Simulated and Experimental Results

Many running trials were simulated to evaluate how important the swing leg velocity modulation is with respect to the locomotion stability. The analysis was made by varying the leg impedance around the ideal one, in order to simulate an imprecise impedance adjustment, and evaluating the variation of the actual duty factor (the actual D_f is used to evaluate the running because it is a normalized index implicitly related to the "flight phase" period). This impedance variation was used for different values of K_v to verify the benefits of modulating the swing leg velocity. The results are shown in Fig. 2 by using box plots associated with the absolute duty factor error for each selected impedance. To better understand the resulting behaviour due to slight impedance variations, Fig. 3 shows the ground reaction forces for two samples taken from Fig. 2.

Different motion profiles were created by associating gait features, e.g. V_f, f_s and D_f, with a respective leg impedance. Having pre-defined profiles allowed the robot to quickly transition between desired forward velocities. Simulated running trots were performed with forward velocities ranging from 0 to 3 m/s, duty factors from 0.35 to 0.45 and K_v from 1 to 2. Figure 4 shows some shots of simulated and experimental running trots.

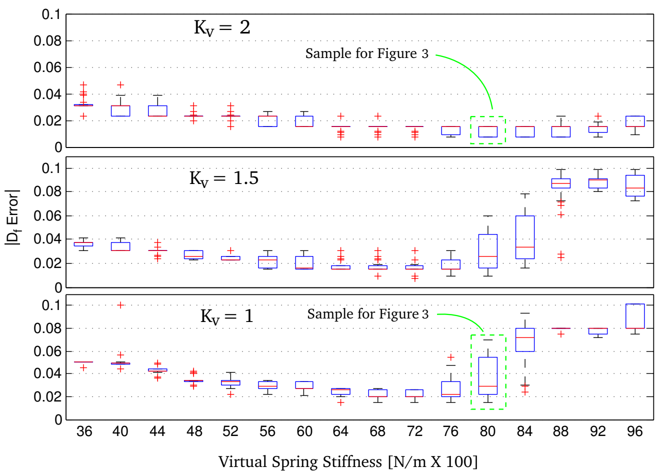


Figure 2: Box plots for absolute duty factor errors according to the stiffness adjustment of the virtual telescopic leg for different values of K_v. The gait features are: $V_f = 0.2m/s$, $H_s = 0.1m$, $f_s = 1.5Hz$ and $D_f = 0.4$. The virtual leg damping is $200Ns/m$ and the ideal stiffness for resonance behaviour is around $6800N/m$.

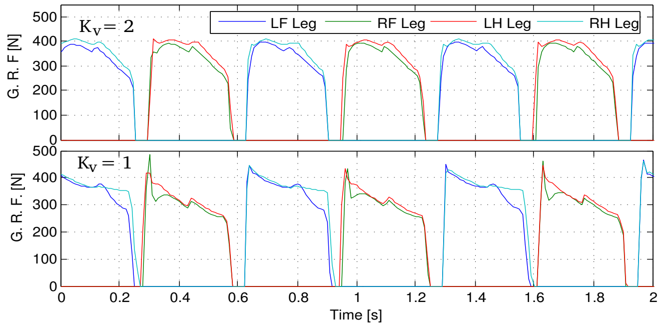


Figure 3: Ground reaction forces for the two samples taken from Fig. 2. Observing the flight phase periods, one verifies that the gait with swing leg modulation ($K_v = 2$) is more robust when the impedance adjustment differs from the ideal one and reduces ground reaction forces during touch-down.

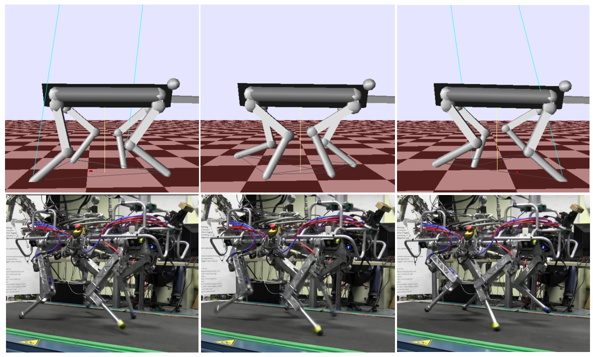


Figure 4: HyQ flight phase during running trot. For the simulated environment the robot trots at 3 m/s with a duty factor equal to 0.35 (top images). On the treadmill the real robot runs at 1 m/s with a duty factor equal to 0.45 (bottom images).

4 Conclusion

The modulation of the swing leg velocity provides locomotion robustness by making running less sensitive to mismatched impedance settings. Moreover, it reduces the ground reaction forces at touch-down minimizing undesired disturbances that may compromise the running stability. The proposed trajectory generation and the creation of motion profiles allowed to achieve higher velocities for a running trot gait.

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