Viscosity-based Height Reflex for Quadrupedal Locomotion on Rough Terrain

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I. Introduction

Legged robots are meant to traverse unstructured environments. In some cases, high steps (level changes) can pose significant challenges. These terrain features can be successfully addressed by *whole body optimization* when a map of the environment is available. Despite recent advances in this field [8], optimal planning is still far from being realized in real time, due to the complexity of the optimization process, the need to have both reasonably accurate 3D maps of the environment [5] and reliable state estimation [3]. In particular these approaches are of limited applicability in cases of visual *deprivation* where a reactive approach is preferable [1, 6]. In this abstract we propose a *height reflex* strategy to successfully negotiate big height changes (e.g. when the robot steps down from a high pallet). In this context, an important issue is the *loss of mobility* of the swing leg, when trying to establish a new foothold during a *reaching* motion [7]. An elegant way to address this situation, is to "squat" the whole trunk to aid the reaching motion. In other words, the swing motion can be "reconfigured" by mapping it among the four legs. This results in a reaching motion without stretching too much the swing leg. Another way of seeing this is that the height reflex is able to extend the workspace of the swing leg, through the motion of the body. This behaviour is somewhat similar to the one presented in [2], but we tackle the problem from a planning perspective rather than a control one. With our approach we were able to address higher obstacles, up to $24cm$ which is 33% of the leg length and 58% of its retractable leg range [9]. The proposed approach is also able to incorporate kinematic limits.

II. Viscosity-based Height Reflex

The *height reflex* is embedded into our statically stable crawl locomotion framework [7]. The reflex is active only during the swing phase, and it replans all feet trajectories when the swing leg is loosing mobility, by exploiting a kinematic model of the robot made of virtual dampers. A feature of this approach is that we can easily regulate the *transfer of motion* by simply tuning the *virtual* damping value for each joint. The height reflex can be seen as setting a "honey-like" environment for the leg which is loosing mobility while reducing "viscosity" for the legs that are in stance that will start to move instead. In the case that a kinematic limit of a joint is hit, the reflex corrects the feet trajectories such that the joint desired positions are clipped at their usable range. In the implementation of the desired height reflex behaviour, we consider a partition of feet variables $\# = \begin{bmatrix}\#_{sw} & \#_{st}\end{bmatrix}$ into the swing part $\#_{sw} \in \mathbb{R}^3$ and the stance part $\#_{st} \in \mathbb{R}^{n-3}$. Where # can be either a *virtual* force $f^r \in \mathbb{R}^n$, the original $x_f^d \in \mathbb{R}^n$, or the reflex-corrected $x_f^r \in \mathbb{R}^n$ feet trajectories, respectively. Since our robot HyQ [9] has 12 degrees of freedom (DoFs)) we will consider $n = 12$. Figure 1 illustrates a detailed schematic of the *height reflex* module. The first step is to map the desired swing foot motion $x^d_{f_{sw}}$ at the force level (e.g. a Cartesian force f^r_{sw}) by mean of a virtual spring (e.g. impedance K_x). Then we map this virtual force at the stance feet in a least-square fashion, considering kinematic feasibility (e.g. no internal forces should be created between the stance legs) and preserving static stability (e.g. only the component of f^r_{sw} along gravity $f^{r\perp}_{sw}$ is mapped). In the mapping we also enforce static equilibrium constraints: 3 constraints for the equilibrium of linear forces $f_i^r \in \mathbb{R}^3$ and 3 constraints for equilibrium of moments (about the swinging point foot) $M_i^r \in \mathbb{R}^3$:

$$\sum_{i \in c_{st}} f_i^r = -f^{r\perp}_{sw} \tag{1}$$

$$\sum_{i \in c_{st}} M_i^r = \sum_{i \in c_{st}} (x^r_{f_i} - x^r_{f_{sw}}) \times f_i^r = m \tag{2}$$

where c_{st} is the set of stance legs index. Then, rewriting (2) in linear form, and adding the stance constraints (3 constraints), we can solve for the stance leg *virtual* forces as $f^r_{st} = A^{-1}b$: Additionally, the orientation of the robot can be regulated (during the squatting motion), by means of a virtual spring that adds a non zero moment m in the momentum equation (2). Then the solution f^r_{st} is given as input to a *virtual* damper model of the robot. This is a massless model of the robot with (variable) viscosity (damping) at the joints (see Fig. 2). A damper model relates a vector of joint torques $\tau^r \in \mathbb{R}^{12}$ to joint velocities $\dot{q}^r \in \mathbb{R}^{12}$ according to the known relationship $\tau_r = D_r \dot{q}_r$. Where $D_r \in \mathbb{R}^{12\times 12}$ is the virtual damping matrix of all the active joints. Therefore, we can compute the new vector of feet positions/velocities x_f^r, $\dot{x}_f^r$ that will be sent (in place of the original plan) to the inverse kinematics module (see Fig. 1):

$$\dot{q}^r = D_r^{-1} \underbrace{\left(J(q^r)^T f^r - \tau_{kl}\right)}_{\tau_r} \tag{3}$$

where $f^r = \begin{bmatrix} f^{rT}_{sw} & f^{rT}_{st}\end{bmatrix}^T$ is the vector of virtual forces and $J \in \mathbb{R}^{12\times 12}$ is the Jacobian matrix of all the feet. The end-stop limits are incorporated as virtual joint torques $\tau_{kl} \in \mathbb{R}^{12}$ generated by virtual springs that push the joints away from their limits.

Damping scheduler. A smart way to spread the swing motion among the legs is to set different damping values for the joints of each leg. The idea is that, by setting a lower viscosity (e.g. damping) for all the joints of a leg, that leg will move more. Our heuristic is to regulate the damping according to the swing leg mobility. As long as the swing leg is losing mobility we gradually increase the damping for the joints of the swing leg, while, in parallel, we reduce it for the joints of the remaining stance legs, in order to *redistribute* the motion over them. We decided to use the *velocity transformation ratio* m [4] as a metric to estimate the mobility of the swing leg.

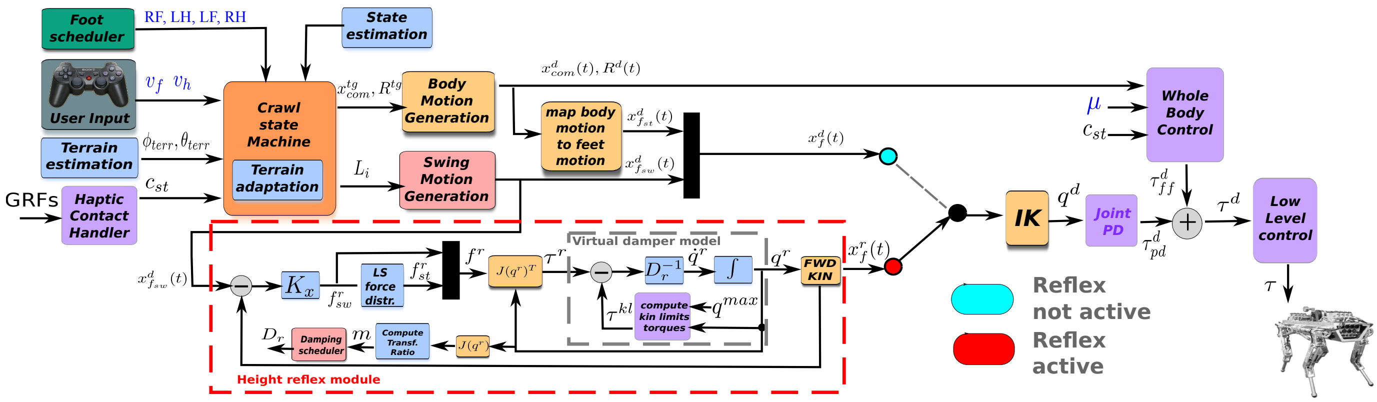

Fig. 1: Block diagram of the locomotion framework with a detail of the *height reflex* module. The input is the originally planned desired swing foot position $x^d_{f_{sw}} \in \mathbb{R}^3$, while the output is the vector of corrected feet positions $x^r_f \in \mathbb{R}^{12}$.

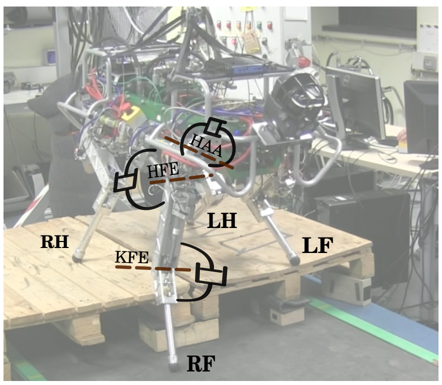

Fig. 2: HyQ robot stepping down from a 24 *cm* height platform. The virtual damper model is shown only for the *RF* leg.

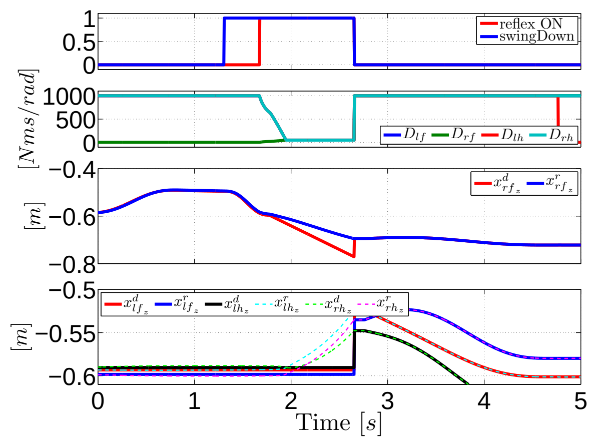

Fig. 3: Experimental data showing the action of the reflex when the *RF* leg is swinging.

III. Results

We present in this section experimental results [1] of our robot HyQ stepping down from a 24*cm* platform (Figure 2). HyQ is a 90 kg hydraulically actuated quadruped robot which has 12 active DoFs and it is fully-torque controlled. The height reflex was fundamental for the success of the task. Figure 3 shows experimental data when the reflex is in action on the *RF* leg (e.g. when this is swinging down from the step). The upper plot shows the *height reflex* activation during the swing down, while the second plot shows the scheduling of the damping according to the mobility loss of the swing leg. The 3-rd and 4-th plot show how the trajectory is modified by the reflex for the swing leg and the stance legs, respectively: part of the swing motion is redirected to the stance legs that retract leading to a squatting of the trunk.

[1] A video of the experiments can be found at https://youtu.be/1gbgAhPu1xs

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