Turning Maneuvers Strategy for Quadrupedal Bounding Gait

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I. Introduction

Legged robots have the potential to outperform existing wheeled machines in terms of versatility since they can move in human tailored environments. However, finding the correct sequence of reference joint positions and feed-forward torque trajectories is not an easy task and many different approaches can be implemented. We concentrated on the bounding gait as an example of a highly dynamical movement which may allow IIT's 80-kg hydraulic quadruped robot HyQ to cover large distances in a reasonably short time also in the presence of terrains of moderate roughness. We present here a module named *linear kinematic adjustment* which enhances the tracking of the reference feet trajectories. Besides that we also describe our implementation of the speed controller which allows our robot to perform omni-directional maneuvers while bounding.

II. Gait baseline optimization

A periodic bounding gait was obtained for HyQ by finding the amplitudes of feed-forward force impulses that realize a periodic limit cycle. The periodic solution was then stabilized by state feedback [1]. A detailed description of the offline optimal control problem can be found at [2].

III. Kinematic adjustment

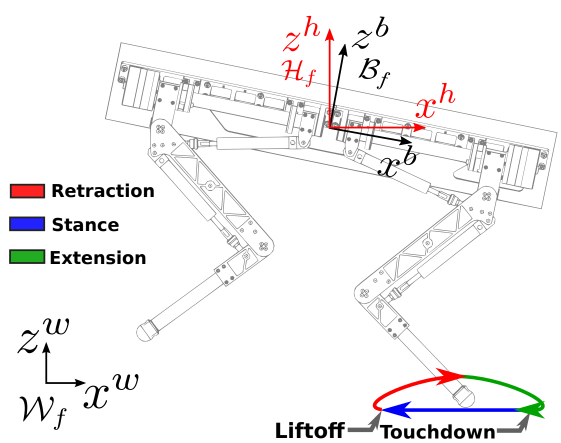

Fig. 1: Foot trajectory for bounding at a given speed $\dot{x}$.

All the foot trajectories and desired CoM trajectory have been computed in the *world frame* $\mathcal{W}_f$ and we denote them by $({}_w\mathbf{x}_f, {}_w\dot{\mathbf{x}}_f)$. The trajectories need to be mapped into the *base frame* $\mathcal{B}_f$ first, before they get fed into the inverse kinematics and finally become joint trajectories $(\mathbf{q}_{des}, \dot{\mathbf{q}}_{des})$. We make use of an intermediate reference frame named *horizontal frame* $\mathcal{H}_f$ [3] which shares the same origin with the $\mathcal{B}_f$ and has the same yaw orientation ψ but it is aligned with gravity. The involved quantities are therefore:

- ${}_w\mathbf{x}_b \in \mathbb{R}^3$ = cartesian base position in $\mathcal{W}_f$;
- ${}_w\mathbf{x}_f \in \mathbb{R}^3$ = cartesian foot position in $\mathcal{W}_f$;
- ${}_h\mathbf{x}_f \in \mathbb{R}^3$ = cartesian foot position in $\mathcal{H}_f$;
- ${}_b\mathbf{x}_f \in \mathbb{R}^3$ = cartesian foot position in $\mathcal{B}_f$.

The *kinematic adjustment* module takes care of this transformation from $\mathcal{W}_f$ to $\mathcal{B}_f$ with the peculiarity of using the *actual state* of the robot rather than the desired state. This decreases the tracking error of the desired feet trajectories by accommodating the compliant motion of the base. When a joint impedance controller is implemented this corresponds to removing the possible conflicts between the legs and the trunk's dynamics. The module is composed of two steps:

- *linear kinematic adjustment:* it is linear translation from $\mathcal{W}_f$ to $\mathcal{H}_f$. This reduces the impacts at touch down and ensures the desired foot clearance during the swing phase:

$$\begin{cases} {}_h\mathbf{x}_f^d = {}_w\mathbf{x}_f^d - {}_w\mathbf{x}_b & (1) \\ {}_h\dot{\mathbf{x}}_f^d = {}_w\dot{\mathbf{x}}_f^d - {}_w\dot{\mathbf{x}}_b & (2) \end{cases}$$

  However, having an accurate knowledge of the base position ${}_w\mathbf{x}_b$ in the fixed world frame is not an easy task, especially for highly dynamic motions like the bounding. In this case slippage may occur or the flight phase may last slightly longer or shorter than expected. A reliable state estimation is thus of paramount importance for the computation of ${}_w\mathbf{x}_b$ and ${}_w\dot{\mathbf{x}}_b$. In absence of such a state estimator or an external ground truth we reset the pose of the world frame at every cycle: we reset the world frame to be coincident with the horizontal frame pose at the latest apex state (i.e. when ${}_h\dot{z}_b^h = 0$). In such a way we neglect the accumulated errors of the past gait cycles and we concentrate on the state of the current cycle.
- *angular kinematic adjustment:* this module performs a rotation ${}_bR_h$ from $\mathcal{H}_f$ to $\mathcal{B}_f$ using the *actual orientation* (roll ϕ and pitch θ) of the trunk as introduced in [3].

It consists in a replanning of the feet trajectory in order to accommodate the trunk rotational motion.

IV. Speed and turning control

Once we obtained the stable periodic bounding gait *in place* and a good tracking performance we pose ourselves the problem of controlling the robot's horizontal and angular speed. For this goal we implemented a speed controller that creates at each gait cycle an offset in the overall linear and angular momentum of the trunk that propels the robot in the desired direction. Let us consider for example the amplitude of the optimal feed-forward impulses $\mathbf{a}_i^* = [a_{i,x}^*, a_{i,y}^*, a_{i,z}^*]^T$ where i is the foot index, i.e.: $i = \{LF, FR, LH, RH\}$ and whose value was found in Section II. The speed controller will take these values and obtain the final amplitude a_i^* depending on the user's desired linear and angular speeds ${}_h\mathbf{x}_b^d$ and $\dot{\psi}^d$:

- angular speed control: $a_{iy} = a_{iy}^* + K_{d,\psi}(\dot{\psi}^d - \dot{\psi})/{}_b x_{f_i}$ where ${}_b x_{f_i}^d$ is the x coordinate of the i^{th} foot in $\mathcal{B}_f$.
- linear speed control: $a_{\mathbf{x}_i} = a_{\mathbf{x}_i}^* + K_{d,\dot{\mathbf{x}}}({}_h\dot{\mathbf{x}}_b^d - {}_h\dot{\mathbf{x}}_b)$

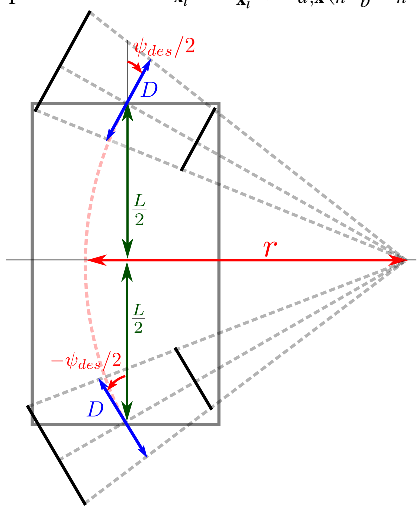

Fig. 2: Top view of the representing the main parameters involved in the computation of the curvature radius r. D is the stride which depends on the desired linear speed ${}_h\dot{\mathbf{x}}_b^d$.

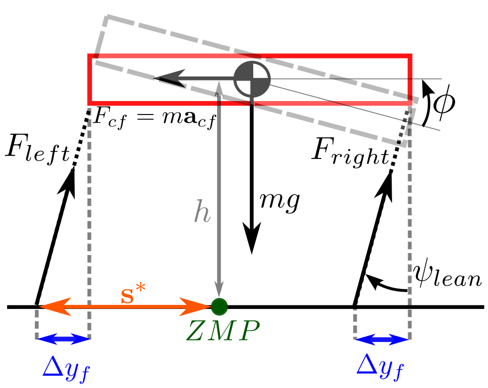

Fig. 3: Rear view of the quadruped robot during a turn to the right. The offset Δy_f restores the stability margin s^*.

Moreover, at high speeds it becomes necessary to take the centrifugal acceleration $\mathbf{a}_{cf}$ into account which gets more and more relevant with the increase of the linear speed ${}_h\dot{\mathbf{x}}_b$ (see Fig. 3):

$$\mathbf{a}_{cf} = \frac{{}_h\dot{\mathbf{x}}_b{}^2}{r} \tag{3}$$

where r where is the instantaneous radius of curvature $r = \frac{{}_h\dot{\mathbf{x}}_b}{\dot{\psi}_{des}}$ and L is the length of the robot's trunk.

The quantity $\mathbf{a}_{cf}$ will unload the legs on the inner side of the turn and will cause a shift of the Center of Pressure (CoP) outwards with respect to the turn. This will reduce the lateral stability margin given by the distance s between the CoP and the foot along the support line of the double stance phase. Our strategy consists in moving the feet laterally of an offset Δy_f to improve the lateral stability margin s^*. As a consequence of this offset Δy_f the legs will take on a certain leaning angle (see Fig. 3) with respect to the normal to the terrain:

$$\varphi_{lean} = atan(\frac{\Delta y_f}{h}) \tag{4}$$

where h is the height of the CoM of the robot. In this way the legs align with the contact forces and no extra torque is applied on the Hip Abduction/Adduction joints (see Fig. 3). Furthermore it is favorable in terms of energy efficiency to roll the trunk of the same leaning angle [4] in such a way that $\phi = \varphi_{lean}$. The legs and the main axis of their manipulability ellipsoids get in this way parallel to the sagittal plane. This strategy was tested both in simulation and on

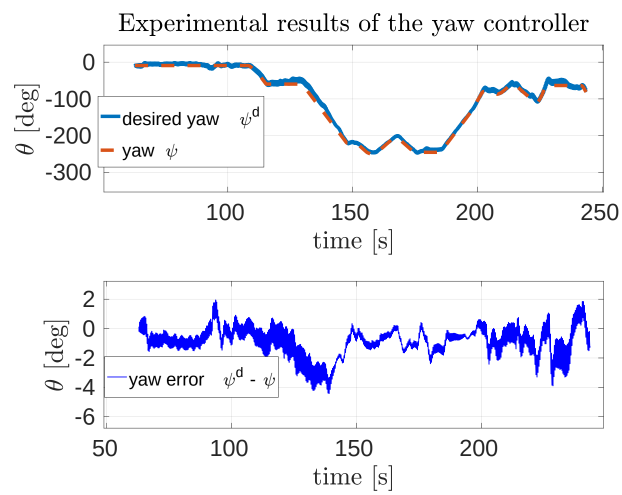

Fig. 4: Experimental data registered on HyQ while turning. (above) tracking of the yaw angle; (below) the yaw error is always below 4deg

the real hardware. Some preliminary test of HyQ performing turning maneuvers while bounding can be seen at this link: https://youtu.be/bHKv3yk3vx8

References

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