Dynamic Trotting on Inclined Terrain for Quadrupedal Robots

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1 Motivation

Locomotion on inclined terrain poses several challenges to legged robots. To avoid slipping and kinematic limits, information about the terrain's inclination is needed to carefully plan footholds and the main body pose, as well as to modulate the ground reaction forces. This is even more challenging for dynamic trotting, as only two legs are supporting the main body and driving the motion at any moment in time. We propose a method for estimating a model of the terrain using only contact sensing paired with internal state estimation that can drift over time. Our improved control framework enabled StarlETH [1], a medium-sized, fully autonomous, torque controllable quadrupedal robot, to trot on slopes of up to 21°.

2 State of the Art

Walking on slopes has been a topic of active interest since the early days of legged robotics [2, 3], and it continues to be heavily researched in recent years [4, 5, 6, 7, 8]. Boston Dynamics BigDog [9] and LS3 have been shown trotting uphill and on rocky slopes, although no experimental data is available and very little is known about the adopted control strategies. Uneven terrain can be treated as a perturbation, thus avoiding the issue of having to model it explicitly. However, this has only been shown to work on relatively modest slopes [10, 11]. A strategy that is commonly employed is to adapt the roll and pitch angle of the robot with respect to the slope. The configuration of the legs can also be adapted. For instance, the extension of the legs can be adapted using neural control systems [12, 4]. For robot legs that exhibit kinematic redundancies, the orientation of the leg segments with respect to the vertical direction can also be adapted, as executed by Lauron [8].

3 Own Approach

We build a model of the environment using the limited perception capabilities of the robot, i.e. optical force sensors at each foot, joint encoders and an inertial measurement unit. Fusing this information through an Extended Kalman Filter [13], we can accurately detect a contact event and its position with respect to the body. We model the environment by fitting a plane in the form $z = ax + by + d$ through the contact points and estimating its parameters a, b and d. As long as at least three non collinear contact points are available, the problem is well defined and parameter estimation is trivial.

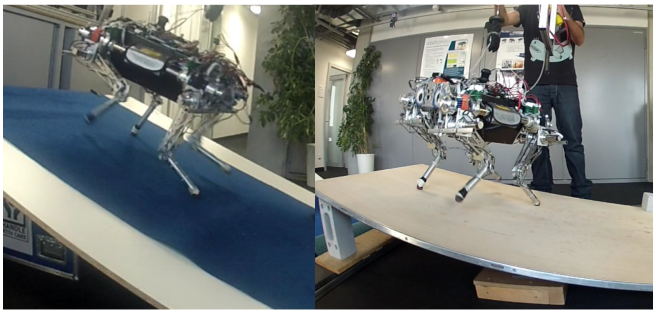

Figure 1: Our quadrupedal robot, StarlETH, employing a dynamic trotting gait to move forward and turn on slopes of up to 21° (38%) with only two legs simultaneously in contact with the ground.

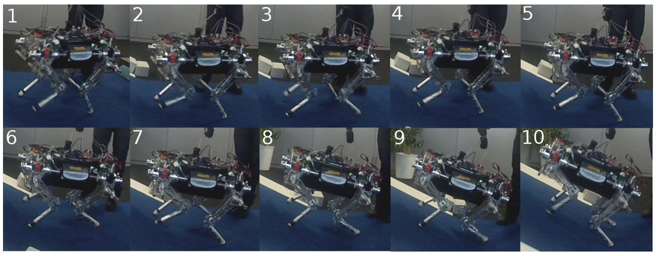

Figure 2: The sequence shows how the robot approaches and adapts its body to a tilted terrain.

However, for the trotting gait that we consider, only two legs are in contact at any moment in time. Our method uses the most recent contact position of each leg to estimate the plane model. The plane parameters are then estimated by means of a least squares technique. In this framework we define a so-called *Control Frame C*. The origin of *C* is fixed to coincide with the World Frame origin. Its orientation follows the the estimated terrain inclination and the heading direction of the robot. By defining the reference signals in this frame, the robot body can automatically adapt to the estimated slope.

4 Current Results

We have succesfully[1] been able to transit from flat to tilted terrain (Fig. 2), as well as turn in place on it (Fig. 1), thus estimating the roll and pitch angle of the plane (Fig. 3). The contribution of this work is an accurate method to extract slope angles and terrain heights using limited perception capabilities. The terrain is modeled as a simple plane, whose parame-

[1]https://youtu.be/NPuHwxpVUpg

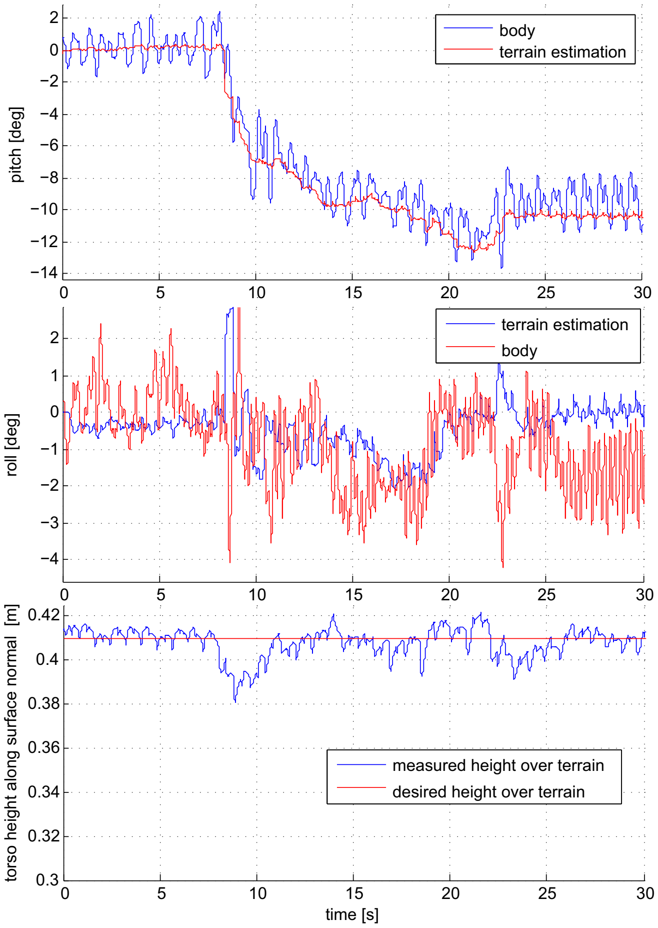

Figure 3: The estimation results of the slope roll and pitch angles.

ters are estimated from a history of footholds in a least-square sense. The proposed method is robust against drifts of measurments of the robot's pose and is applicable for dynamic gaits.

5 Best Possible Outcome

The foot placement strategy we employ places the feet relative to the hip vertically projected on the ground. Our approach to locomotion on inclined terrain can be extended by examining the so-called lever mechanism [14], where the footholds would be placed relative to the hips projected along the normal to the terrain. This method could provide better body orientation and limit the issues caused by approaching kinematic limits on steep slopes.

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