Inverse dynamics with optimal distribution of contact forces for the control of legged robots

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1 Introduction

In addition to well-thought mechanical designs, there is a need for advanced control algorithms that can provide the versatility needed to locomote on difficult, potentially extreme terrains. Such a controller should offer two important features: high tracking performance to guarantee precise feet and hand placements when needed and control of contact forces created by the robot on its environment. Contact forces play a very important role for locomotion on difficult terrain. For example, when the robot is walking on a slippery terrain the controller can minimize tangential contact forces to prevent slipping, or create specific contact forces to locomote on terrains that require close to climbing motions. In this presentation, we would like to discuss a new inverse dynamics controller that can guarantee both high tracking performances and an optimal control of contact forces at the same time [6]. The controller can dramatically improve the locomotion of robots on difficult terrains and is simple and robust enough to be used in fast control loops.

2 Related work

The problem of contact force distribution during locomotion has already been addressed in the literature [3, 4]. Hyon et al. [2] proposed a force control approach to control the balance of a humanoid robot. The algorithm directly controls desired contact forces with the environment to achieve a desired task (e.g. a balance task). The advantage of such an approach is that it does not require a full dynamic model of the robot. However the controller is derived assuming a static robot and therefore cannot take into account fast robot motions. Stephens et al. [9] also proposed a force control approach for the balance of a humanoid robot. The method computes joint torques to achieve a desired contact forces objective using a dynamic model of the robot and constrained optimization algorithms. A potential desired motion is then treated as a secondary objective. In these cases, the manipulation of contact forces is done as a primary goal, for example to create balance controllers. It is in contrast with the present contribution that aim at creating tracking controllers able to manipulate contact forces using torque redundancy, i.e. motion control is our primary goal.

Several model-based controllers such as inverse dynamics or operational space control were recently proposed for floating-base[1] robots subject to contact interaction with the environment [1, 5, 8]. These controllers are used to efficiently track desired trajectories while guaranteeing a certain level of compliance due to reduced feedback gains. The method proposed in [5] is of special interest since it does not require a structured representation of the dynamics (i.e. no need to compute individual components like the inertia matrix, Coriolis, and gravity terms) and mainly relies on kinematic quantities, which makes it particularly robust to uncertainties in parameter estimation and, additionally, computationally very effective. It is the method that we use to derive our controller.

3 Optimization of contact forces

Interestingly when there are more than six contact constraints with the environment, the inverse dynamics problem is under-determined in the sense that there is an infinite number of torque commands for a constraint-consistent desired motion. It is the case, for example, when a biped has its two feet on the ground or when a quadruped robot with point feet has more than two feet on the ground. There are more degrees of freedom for the actuation than for the possible motions due to the constraints imposed by the contacts. The over-constrained case is very interesting because there is an infinite number of possible choice of commands to realize a desired motion. In general, redundancy is resolved by minimizing a cost criterion, e.g., a quadratic cost in the commands as in [5, 7]. Recently we showed how to use torque redundancy to directly manipulate the contact forces instead [6]. We can then create tracking controllers optimal with respect to any combination of linear and quadratic costs of the contact forces.

Such a result is particularly relevant for legged robots as it allows to use torque redundancy to directly optimize contact interactions. For example, given a desired locomotion behavior, it can guarantee the minimization of contact forces to reduce slipping on difficult terrains while ensuring high tracking performance of the desired motion. More generally, it can be used to track both desired joint motions and

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[1] We refer to floating base robots as robots that are not fixed to the ground due to their 6 non-actuated DOFs that describe the position and orientation of the robot relative to an inertial frame.

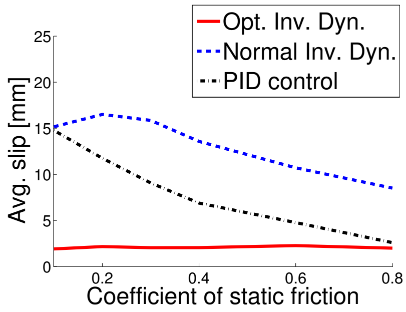

Figure 1: The figure shows the average slipping for a quadruped robot walking on terrains with different friction coefficients. The same exact joint trajectories are used in three different experiments where a different tracking controller is tested: a high gain PID controller (black), an inverse dynamics minimizing the total torque (blue) and the inverse dynamics controller minimizing tangential reaction forces (red). This illustrates the importance of the control to improve locomotion.

contact forces to balance the robot in a more efficient way or to create more dynamic motions.

The proposed controller is very simple and computationally efficient and can therefore be implemented in a high bandwidth torque control system. We present detailed simulations of the Sarcos Humanoid robot and the Boston Dynamics Little Dog robot to illustrate the capabilities of the controller. We find that it can greatly improve the locomotion on difficult terrains without changing the planned joint trajectories by just taking advantage of the redundancy present at the torque level (cf. Figure 1). Experiments on the Little Dog platform demonstrate that the controller is suitable for real-world applications where we don't have a perfect dynamic model of the robot.

4 Discussion

Our controller offers an elegant approach for force optimization from an inverse dynamics control perspective. It demonstrates the importance of control approaches to improve locomotion performance and reminds us that motion planning is not sufficient. It would be interesting to discuss how such controllers could be integrated with planning algorithms. Local optimality results from the controller could be used to create more optimized motion plans that are tightly integrated with the control. A far reaching application would be the integration of such a controller as the low-level component of a model predictive control structure. Also, it is not completely clear how our approach compares with the force control approaches discussed before and this would constitute an interesting topic of discussion at the conference. More specifically, it would be interesting to understand what these methods can and cannot provide for the control of dynamic walkers. For example, our approach can naturally be extended for the control of robots with passive elements and could potentially offer a way to control dynamic walkers. The manipulation of contact forces in an optimal way could be used to improve locomotion efficiency and stability.

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