

Compliant Walking using Floating Base Inverse Dynamics

Michael Mistry^{*†}, Jonas Buchli[†], Mrinal Kalakrishnan[†], Peter Pastor[†], Sang-ho Hyon^{*} and Stefan Schaal^{†‡*}

Summary

We introduce a new method for model based control of floating base systems, such as walking robots. Model based control allows for high compliance without sacrificing tracking accuracy, which is critical for robust walking over rough terrain. Using an orthogonal decomposition, we project the robot dynamics into a reduced dimensional space, independent of contact forces. Doing so allows us to compute the analytically correct inverse dynamics torques, providing a practical solution for the ill-posed problem of floating base inverse dynamics. Such controllers allow for compliant control, thus improving robustness in case of unperceived or wrongly perceived obstacles and the safety of robots when operating among humans. Our approach shows graceful degradation in case of model inaccuracies (avoiding the inversion of the RBD inertia matrix) and/or violation of the analytical assumptions made in the derivation of the controller. Therefore, our approach is usable on real systems. We demonstrate the feasibility and robustness of our approach on a stepping simulated floating base bipedal humanoid robot and an actual robot dog locomoting over rough terrain.

Introduction

Compliant control is a hallmark of biological movement generation, and will be mandatory if future robots are to share human environments in a safe way such that the robot can robustly give-in in case of unforeseen disturbances or obstacles in its path. Model-based control is needed for compliant control to achieve control accuracy, but model-based control on floating base robots, e.g., legged robots such as humanoids, is non-trivial due to under-actuation, dynamically changing constraints from the environment, and potential closed loop kinematics. Our previous inverse dynamics approach relied on estimation of contact forces to compute an approximate inverse dynamics solution. Here we present an analytically correct solution by using an orthogonal decomposition to project the robot dynamics into a reduced dimensional space, independent of contact forces.

Methods

When a floating base robot is in contact with the environment, the full equations of motion with respect to an inertial frame are given by

$$\mathbf{M}(\mathbf{q})\ddot{\mathbf{q}} + \mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) = \mathbf{S}^T \boldsymbol{\tau} + \mathbf{J}_C^T(\mathbf{q})\boldsymbol{\lambda} \quad (1)$$

with variables defined as follows:

- \mathbf{q} is the floating base configuration vector (the robot DOFs + the 6 DOFs base)
- $\mathbf{M}(\mathbf{q}) \in \mathbb{R}^{n+6 \times n+6}$: the floating base inertia matrix

- $\mathbf{h}(\mathbf{q}, \dot{\mathbf{q}}) \in \mathbb{R}^{n+6}$: the floating base centripetal, Coriolis, and gravity forces.
- $\mathbf{S} = \begin{bmatrix} \mathbf{I}_{n \times n} & \mathbf{0}_{n \times 6} \end{bmatrix}$: the actuated joint selection matrix
- $\boldsymbol{\tau} \in \mathbb{R}^n$: the vector of actuated joint torques
- $\mathbf{J}_C \in \mathbb{R}^{k \times n+6}$: the Jacobian of k constraints
- $\boldsymbol{\lambda} \in \mathbb{R}^k$: the vector of contact forces

The goal of inverse dynamics is to compute the joint torques that will realize a desired joint acceleration, $\ddot{\mathbf{q}}_d$, given the current state $(\mathbf{q}, \dot{\mathbf{q}})$ of the robot. Note that this problem is ill-posed. However, we can show that a solution can be obtained via an orthogonal decomposition of the constraint Jacobian:

$$\boldsymbol{\tau} = (\mathbf{S}_u \mathbf{Q}^T \mathbf{S}^T)^+ \mathbf{S}_u \mathbf{Q}^T [\mathbf{M}\ddot{\mathbf{q}}_d + \mathbf{h}] \quad (2)$$

where \mathbf{Q} is obtained from the \mathbf{QR} decomposition of \mathbf{J}_C , and $\mathbf{S}_u = \begin{bmatrix} \mathbf{0}_{(n+6-k) \times k} & \mathbf{I}_{(n+6-k) \times (n+6-k)} \end{bmatrix}$. Note that this expression is independent of the contact forces, a significant benefit over contact force sensing or estimation.

Results and Discussions

We use the SL simulated bipedal robot, modeled after the lower half of the CBi humanoid robot, developed by SARCOS Corporation and the ATR Computational Neuroscience Laboratories. The simulated robot has 2×7 DOF legs and a 1×2 DOF torso, for a total of 16 DOF. The robot has a free floating base, and is only constrained by its contacts with the floor (using a spring-damper contact model). First we demonstrate how floating base inverse dynamics can improve joint tracking performance of the biped robot, while keeping feedback gains low and joints compliant. Next we show how floating base inverse dynamics can be used to modify joint tracking control in order to achieve an operational space objective. In this case, we execute a periodic stepping motion in joint space (from a central pattern generator), while maintaining stability using a feedforward balance controller in operational space. The stepping pattern demonstrates the technique's robustness to constraint switching (making and breaking contacts with the feet). We also push the robot to test the balance controller, and demonstrate that we can operate with stretched knee postures. Furthermore, we evaluated our floating base inverse dynamics

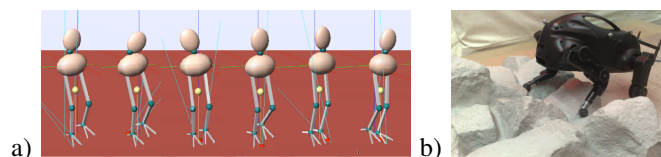


Fig. 1. Reaction of the biped during a 200 N external disturbance, and a constraint switch from the right to left foot. Time progress from left frame to the right. (b) Boston Dynamics LittleDog quadruped robot

controller on the actual LittleDog robot, a roughly 0.3 meter long and 0.2 meter tall robot dog that walks over rough terrain. We demonstrate how floating base inverse dynamics allows us to operate the robot at very low feedback gains and with high compliance. Because of the improved compliance, the robot can traverse unseen obstacles, and complex terrain it is unaware of.

^{*}ATR Computational Neuroscience Laboratories, Kyoto 619-0228, Japan

[†]Computer Science, University of Southern California, Los Angeles, CA 90089, USA

[‡]Neuroscience and Biomedical Engineering, University of Southern California, Los Angeles, CA 90089, USA