Full Dynamics LQR Control for Bipedal Walking

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1 Motivation

Biped robots that are expected to locomote in human environments require whole-body controllers that can offer precise tracking and well-defined disturbance rejection behavior. Although walking is a complex dynamical task involving both hybrid dynamics and underactuation, it is unclear the level of complexity needed to generate and execute these tasks. Previously in [4], we experimentally evaluated the use of a linear quadratic regulator (LQR) using a linearization of the full robot dynamics together with the contact constraints for static poses. The advantage of the controller is that it explicitly takes into account the coupling between the different joints to create optimal feedback controllers for whole-body coordination. Additionally, this control policy is computationally light weight and shows a reliable push recovery behavior competitive with more sophisticated balance controllers, rejecting impulses up to 11.7 Ns with peak forces of 650 N. Our preliminary results on balancing were very encouraging and we are now exploring how these results can extend to more dynamic tasks such as walking. The major contribution of this work will be an exploration in the of the amount of complexity needed to create whole-body motions for walking.

2 Approach

In [4], we derived the linear optimal control framework for a constrained underactuated system tracking static poses. In this work, we conducted experimental tests with a LQR controller using linearized dynamics consistent with contact constraints. The results from these balancing experiments, specifically looking at the impulse that can be rejected, were competitive with state of the art approaches using more involved controllers [2, 5]. In addition, compared to more complex controllers such hierarchical quadratic programs (QPs) [2], our algorithm is computationally extremely cheap. In addition, we showed that this framework can also control higher level objectives such as the center of mass (CoM) and angular momentum by including these quantities in our state cost. We have since generalized the derivation to tracking poses with non-zero velocities and would like to experimentally explore extending this controller to achieve more dynamic movements such as walking. We believe that it may be sufficient to linearize around a couple of key poses that are representative of the dynamics of the robot at the current state. What is unclear, is how much motion each linearization can account for

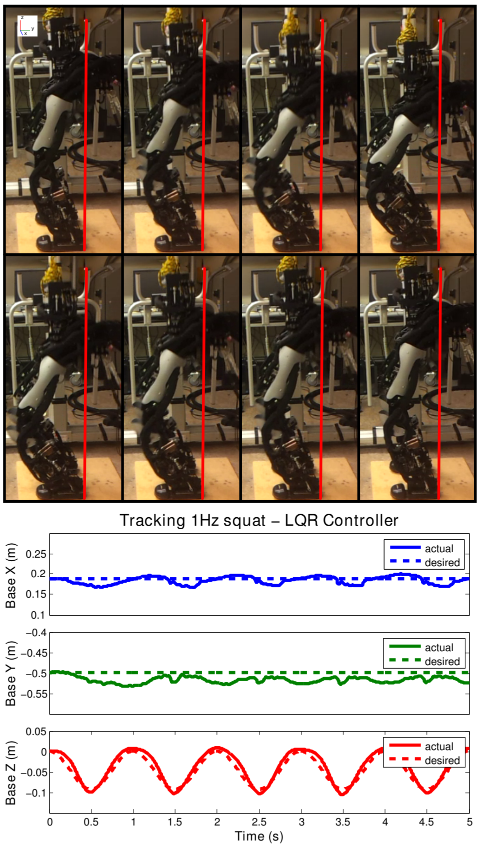

Figure 1: Tracking a 1 Hz squatting trajectory along the Z-axis using a linearization around a single pose to generate LQR gains (i.e. constant gains and feed-forward torques).

(i.e. how many key poses are needed)? A finite control problem can be used in a similar matter, where for a certain range of motion only a single linear model is considered and optimization is performed over a portion of the desired trajectory.

3 Preliminary Results

In [4], we were able to track a squatting trajectory using a single linearization and static gains provided by an infinite horizon control problem, Fig. 1. In this experiment, tracking of a squatting trajectory up to 1 Hz was achieved while also providing some disturbance rejection to small pushes. To extend this for more dynamic motions, we are first considering using linearized dynamics around key poses, with the correspond-

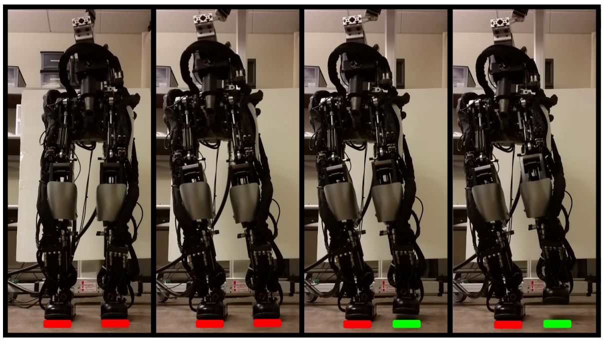

Figure 2: Lower body of hydraulically actuated torque controlled Sarcos humanoid during stepping motion. Red signifies that the foot is constrained to not move in the dynamics equation and green signifies that the foot is unconstrained. This is an example of key poses and constraint conditions that could be linearized around and used to generate gains for the LQR controller.

ing constraints, such as those seen in Fig. 2. To generate a preliminary nominal walking gait to test the whole-body controller, we implemented zero-moment point (ZMP) walking with preview control [3]. While the experiments will be conducted for a ZMP walk, other walking methods, such as [1, 6], could be used. To serve as a benchmark to compare against the LQR controller we use a PD controller (i.e. no coupling among states) that follows joint trajectories from preview control and inverse kinematics. The LQR formulation will allow one to place more importance on CoM tracking, which is not possible for the case of a PD controller. In addition, we believe that by considering the changing dynamics of the system a LQR control framework will perform much better than using fixed PD gains.

4 Potential Discussion Points

We are very interested in discussing the idea of complexity versus performance for control methods that show experimental results on real hardware. We would like to dissect the features that are most critical to include in control algorithms from those that provide little improvement. Along these lines, since our experiments are conducted on real hardware subject to real world conditions, ideas on how to properly design experiments to show generalizable significance as well as dealing with real world issues (i.e. model uncertainty, sensor noise, imperfect state estimation, etc.) would be welcomed. A final noteworthy point of discussion is to analyze the synergies that come out of the optimal feedback gains based on the robot dynamics. Natural balancing strategies for a controller with high base tracking cost are visible in Fig. 3. In the columns corresponding to the base, we can see that all the ankle and knee joints are inversely coupled to the ankle abduction-adduction (AA) joints when rejecting disturbances in the frontal plane (base x). Secondly, the ankle and knee flexion-extension (FE) joints are used almost exclusively for rejecting disturbances in the sagittal plane (base y). These balancing strategies are intuitive for the static case but raise a number of questions for tracking more dynamic movements, namely: 1) How do these synergies change as the robot's dynamics change? and 2) How do these synergies compare to those found among joints in humans?

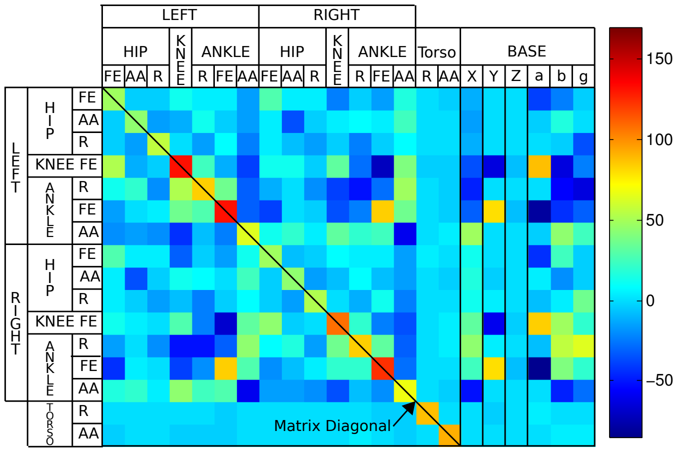

Figure 3: Visualization of the gain matrix for the LQR controller corresponding to the position error (torques on left, states on top), where the variables a,b,g are the cardan angles of the base.

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