Cornell Ranger: Implementing energy-optimal trajectory control using low information, reflex-based control

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1 Introduction

A growing community of researchers have been using optimal trajectory control to generate walking gaits for legged robots (for example Bessonnet 2005 [1], Chevallereau 1999 [2] and 2002 [3], Djoudi 2006 [4], Hardt 1999 [5], Mombaur 2005 [6] and 2009 [7], Roussel 1997 [8] and 1998 [9]).

In optimal trajectory control, one formulates an optimization problem in which one is interested in minimizing a certain criteria like, say, energy used per unit distance travelled subject to various constraints like say walking speed, no foot scuffing, respecting actuator bounds and so forth. The optimal trajectory problem is then cast into a parameter optimization by, e.g., finding control torques as a piecewise linear function of time and then optimizing using one or another numerical method. Assuming numerical convergence to a unique local minimum, a sufficiently fine grid size, usually associated with a large number of control parameters, ensures a reasonably accurate approximation to the true solution.

2 Motivation

Experimentalist who want to implement the optimal trajectory control on a physical robot have to deal with two issues.

1. **A large number of control parameters:** As pointed out earlier, a fine grid has large number of parameters and is a better approximation to the infinite dimensional optimal control problem and hence gives a better solution.
2. **The stability of the optimal trajectory solution:** Optimal trajectory control is not concerned with stability (unless stability is criteria or a constraint in optimization) and the resulting trajectory may or may not be stable. If the trajectory is unstable, than it needs stabilization. The common approach to stabilizing the optimal trajectory is to use a high bandwidth feedback controller that tries to track the optimal trajectory exactly. This type of control introduces another large set of control parameters and if not tuned properly could lead to robot jitter.

3 Methods

We propose the following approach to deal with the above two issues [10, 11].

1. Using the fine grid optimization as a guide, we re-parameterize the controls either as a function of time or of state and re-compute the optimal solution. If we are not reasonably close to the optimal value calculated from the fine-grid optimization, we re-parameterize by adding more parameters or changing the functional form of the representation as needed. Our goal in this step is to simplify the parameterization typically at the cost of loosing a bit of the optimality.
2. In order to stabilize the optimal trajectory, we use an event-based discrete intermittent feed-forward stabilizing controller. In our stabilizing controller, we regulate key heuristically chosen quantities like step length, step velocity once per step using as little sensor information.

We call our control method "reflex-based" because various events are triggered by thresholds in dynamic state variables and they set off more-or-less open loop motor programs.

4 Results

We shows results of our proposed methodology on the bipedal robot called the Ranger [12]. We assume and fit a physics based model of the robot (see [13]). We then solve an energy-optimal trajectory control problem with our cost metric defined as the Total Cost Of Transport (TCOT = energy used per unit weight per unit distance moved) (see [14]). Our energy-optimal control solution had 126 control parameters and predicted a TCOT of 0.167. Next, we simplified the optimal control parameterization based on results from the fine grid optimization. We managed to decrease the control parameters to 15 (factor of 8 decrease) while TCOT increased to 0.18 (an 8% increase). Our simplified control solution was not stable enough to implement on the robot. So next, we added an event-driven discrete intermittent feed-forward controller that tries to regulate the velocity of the robot at mid-stance by regulating the push-off and foot placement. Our implemented control solution on the robot had 30 parameter in all and a TCOT of 0.19 (a 14 % increase from the fine-grid optimum). To date, this is the lowest TCOT ever achieved on any legged robot.

5 Keywords

Experimental bipedal, Energy-optimal control.

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