Fast Multi-Body Simulations of Robots Controlled with Error Feedback

John Shepherd, Samuel Zapolsky, and Evan M. Drumwright

Abstract—**Roboticists modeling control of manipulator and legged robots often assume force/torque-based control using an open-loop model of voltage, hydraulic pressure, or pneumatic pressure to actuate torques. This work shows that such force/torque-based models can lead to stiff differential equations, which are computationally inefficient to solve: relatively small integration steps are necessary to ensure stability.**

We have investigated two approaches which appear to mitigate this problem: incorporating transmission modeling (applicable only to electromagnetic actuators at present) and applying inverse dynamics control. Both of these approaches require increased computation per integration step, but this work will demonstrate that the larger integration steps can still yield considerably higher simulation throughput.

This paper will also identify research challenges with using inverse dynamics control within multi-rigid body simulations. We examine a state of the art approach concerning inverse dynamics control. We integrate the simulation subject to contact and inverse dynamics constraints, and we also identify algorithmic challenges, both theoretical and practical. Experimental virtual robot platforms include a UR10 arm with attached prismatic manipulator and a locomoting quadrupedal robot.

I. Introduction

Roboticists often wish to simulate controlled systems rapidly while prototyping control schemes and hardware designs. In these cases, reducing the duration of the "edit-compile-test" cycle is more important than reducing numerical solution error, which roboticists might do after obtaining some confidence in their approach.

The present study started from the observation that simulating robots with few degrees of freedom and controlled via error feedback could admit large integration steps. These large integration steps can yield much faster simulations at the expense of lower numerical accuracy. Accordingly, this paper tests the following hypotheses:

Hypothesis 1: Driving a multi-body system (e.g., a robot interacting through contact with one or more rigid bodies) through inverse dynamics control can yield greater numerical stability than tuned PD/PID control can offer.

Hypothesis 2: Integrating a multi-body system that accounts for both contact and inverse dynamics constraints yields greater numerical stability than feeding the output from an inverse dynamics controller into the simulation's integrator.

Hypothesis 3: Incorporating transmission models for electromagnetic actuators can increase numerical stability for simulations of robotic systems driven by PD/PID control.

II. Experiments

Simulation experiments were conducted using the multi-rigid body dynamics library *Moby*. The robots used in the experiments were the UR10 arm (sourced from an existing open source ROS package), see Figure 2, and a floating base quadruped model described in existing work [4]. The UR10 arm and attached prismatic manipulator, together, possess eight degrees-of-freedom (DoF), all controllable. The quadruped model possesses 18 DoF, 12 of which are controllable.

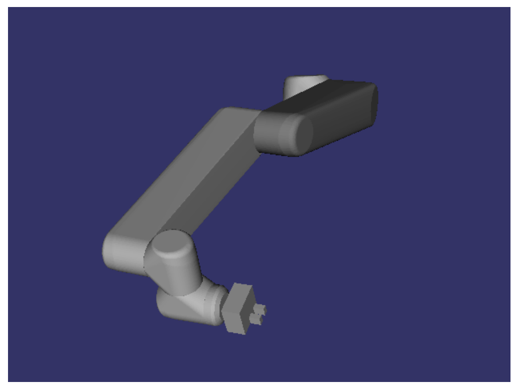


Fig. 2. The UR10 arm with attached prismatic gripper in simulation.

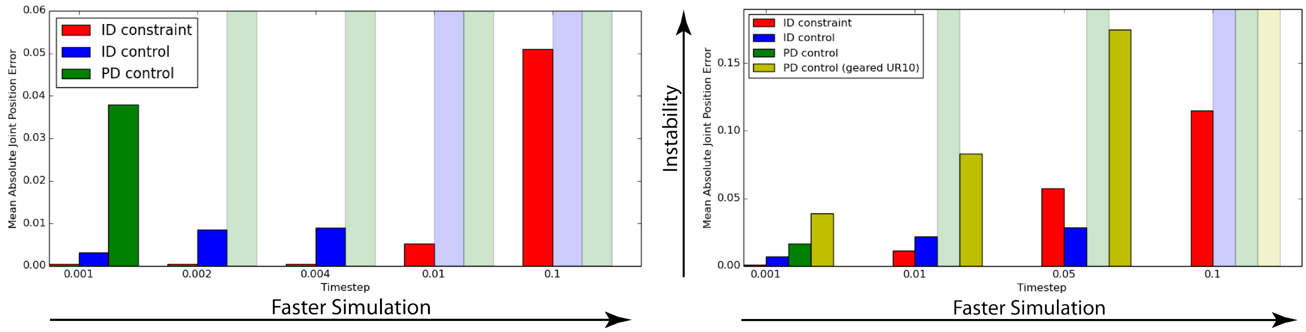
For control testing, the UR10 was directed to follow a sinusoidal motion at each joint. A PD control was used in these experiments, and the gains for the control were tuned by a two-part process consisting of manual tuning followed by nonlinear optimization. The gains were tuned in this way to eliminate human bias to the greatest extent possible.

Integration steps were limited, albeit arbitrarily, to a maximum of 0.1s. The initial integration step size tested for each model was 0.001, a value that we confirmed produced stable simulations of each model readily. Step sizes were doubled until instability resulted.

A. Testing Hypothesis 1: incorporating inverse dynamics control leads to more stable simulations than error feedback control

A PD-controlled UR10 arm served as one experimental control for Hypothesis 1. The maximum step size we attained using this controller without the simulation becoming unstable was 0.001. On the other hand, we found that we could simulate the UR10 arm stably without any controls applied (i.e., the robot falls under the influence of gravity) with a step size of 0.1. An experimental control in a second experiment used the quadrupedal robot model driven by PD control.

In both experiments, the ID control was able to achieve a higher timestep than the PD control. Figure 1 (a) shows



(a)

(b)

Fig. 1. (a). The mean absolute joint position error for the ID constraint, ID control, PD control and geared PD control for the UR10 at various timesteps. A transparent bar indicates instability for the control at the given timestep. Note that the PD control is unstable for all timesteps greater than 0.001. The ID constraint controller is significantly more stable at orders of magnitude larger step sizes than the other controllers. It remains stable when the timestep is at the maximum tested 0.1. The geared UR10 with PD control is able to achieve significantly higher timesteps than standard PD control at the cost of controller accuracy.

that during the quadruped experiment, the ID control was able to achieve a maximum stable timestep of 0.004. The PD control, on the other hand was only able to achieve a maximum timestep of 0.001. Part (b) shows the ID control being able to achieve a timestep of 0.05 when the sinusoidal motion was run on the UR10 arm. PD control was still only able to achieve a maximum step size of 0.001.

B. Testing Hypothesis 2: incorporating inverse dynamics constraints leads to more stable simulations than using inverse dynamics control

We used the inverse dynamics controllers employed as the experimental variables in our tests of Hypothesis 1 as the experimental controls in our tests of Hypothesis 2. For the variables in this experiment, we tested the UR10 arm and the quadrupedal robot. We also tested the quadrupedal robot using an experimental, optimization-based constraint solver.

For the UR10 at a timestep of 0.01, the use of inverse dynamics constraints is able to achieve around the same order of accuracy as the PD control at a timestep of 0.001. Incorporating ID constraints into the UR10 simulation process executed in 2.85s at a 0.01 timestep, while the PD controlled arm required 357.02s at a 0.001 timestep. ID constraints achieved a 125x speedup with essentially the same accuracy.

C. Testing Hypothesis 3: incorporating transmission models increases the stability of robots driven by error feedback control

Claude Lacoursière suggested in personal communication that adding gearing to a robot model might reduce the stiffness in the differential equations. Accordingly, we compared the PD controlled UR10 used to test Hypothesis 1 to a PD controlled UR10 with a virtual transmission modeled at each revolute joint; the gains were re-tuned for this modified model. Gearing was not added to our quadrupedal model because significant architectural modifications would be necessary in our robot's locomotion software to accommodate gearing. Data did indicate that the gearing does dramatically increase the maximum stable step size, at a clear cost of tracking accuracy.

III. Discussion

We have demonstrated the capability of inverse dynamics to dramatically speed multi-rigid body simulations with contact. In our experiments, the maximum stable integration step sizes were tens or hundreds of times larger, thereby permitting much faster simulations. We have also shown that incorporating constraints into the constraint solver for control is less likely to cause simulation instability.

It is clear that important work still remains, particularly in finding a computationally tractable model that produces reasonably accurate contact forces and satisfies inverse dynamics constraints as well as force/torque limits. In the meantime, adding gearing to robots with electromagnetic actuators can provide the requisite simulation stability necessary for high frequency (realtime and above) simulation, albeit with far lower tracking accuracy.

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