Detecting divergent robot behavior with multi-rigid body simulation and random sampling

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I. INTRODUCTION

The motion of robots and objects in our world is often highly dependent upon contact. When contact is expected but does not occur or when contact is not expected but does occur, robot behavior diverges from plan, often disastrously. We describe an approach that uses multi-rigid body simulation with contact toward predicting likely such behavioral divergences on real robots. Our approach, and others like it, could be applied to validation of robot behaviors, mechanism design, and even online planning.

The standard approach to validating robot behavior is simulation followed by in situ testing. This approach does not inspire confidence, though, as simulations often fail to reflect real world behavior (we posit the cause below), and in situ testing is too tedious and slow to perform more than a few trials. This problem has instigated research into formal verification methods for robotics (e.g., [5], [7]), which appears promising; intense study is currently underway to scale these approaches to higher degree of freedom systems. We have been exploring an alternative path that is straightforward, easily implemented, and uses techniques already familiar to many roboticists (see [1], [4]) to bridge typical multi-body simulation tests and extensive testing on real robotic hardware. This approach uses multiple multi-body simulations with perturbations to initial conditions, modeling parameters, and sensory data toward capturing the likely span of situated robot behavior. Early experimental results indicate promise.

II. APPROACH

This section introduces our work on detecting likely divergent behavior in simulations.

Observation: A robot’s behavior is likely to diverge from predicted behavior if unexpected nonsmooth events occur or nonsmooth events occur in novel sequences.

Small modeling errors, differences in initial conditions, or both should be insignificant in the presence of effective feedback control. However, we have noticed that nonsmooth events may rapidly drive the robot outside the region of controller or plan validity. Accordingly, our approach searches for both “grazing” events (events likely to occur in only very particular conditions) and near-miss events, collectively known in hybrid systems literature as “grazing bifurcations” [3]. When a robot is operating around such regions of state space, outcomes will generally be challenging to predict. Examples of this phenomenon are that a slightly longer leg than is modeled might cause the foot to scuff the floor unexpectedly during a step and that a foot heavier than its model might cause tripping on a step when climbing stairs.

Hypothesis: Sampling from a distribution of state, model, and sensor errors may uncover possible divergent behavior of a task to be performed in situ.

We sample modeling parameters and initial state from probability distributions. For robot locomotion, we have used Gaussian and uniform distributions with variances chosen to effect a factor of safety. In a Monte Carlo manner, our strategy generates a probability distribution over the state space that ideally resembles the distribution from conducting physical experiments with the robot (assuming that the physical models are sufficiently representative).

While many robotic systems stymie attempts at quantitatively accurate modeling, constructing models that balance accuracy, parameter identifiability, computational efficiency has been a mainstay of robotics research for decades. Accordingly, we have already observed a probability distribution that effectively describes a complex physical robot’s behavior using our method (see experiment in Section III-A).

III. EXPERIMENTS

The Monte Carlo approach can be applied to various, high-dimensional, non-smooth robotics applications. We chose locomotion experiments to demonstrate the approach because of the hybrid dynamics nature of locomotion tasks that exhibit constant making and breaking of contact and possibility of unexpected collisions. We used the physical simulator Moby, which has been shown to produce behavior consistent with real robots [2], because it uses continuous collision detection [6] that allows it to locate hard-to-find contact events (see [8]).

A. Indication that real behavior is captured

This experiment provides evidence that we can replicate some gross behavioral phenomena between simulation and in situ: walking for exactly $n$ seconds before falling by searching along the range of valid gait periods. We selected this high-level task intuitively, as we did not expect simulation and in situ performance to match quantitatively. Figure 1 indicates a high degree of agreement between simulated and in situ performance. Both the simulated and physically situated robots exhibit decreasing stability for parameter values above 1.0 until a fall is detected after several seconds of walking in situ (for gait period 1.1). Likewise, a fall is detected for the first time at gait period 1.1 seconds in simulation. At period 1.1 seconds, the mean walking time in simulation best matches the
observed walking time in situ (see Figure 2). This experiment provides evidence that bolsters our hypothesis.

![Gait period vs. Runtime](image1)

**Fig. 1.** The average time before a fall versus gait period duration.

![Robot Roll vs Time](image2)

**Fig. 2.** Roll orientation data for the *Links* robot walking in a circle: (Top) in situ [one sample] and (Bottom) in simulation [16 samples]. Each line is labeled with its corresponding value for the gait period duration.

**B. Detecting divergent behavior**

We also conducted an experiment that assesses the ability of a simulation to help locate grazing bifurcations. In the experiment, *Links* walks over a curb obstacle (see Figure 3), passing in close proximity to the obstacle as it moves. We hypothesized that a grazing bifurcation would be present when the step height is approximately equal to the obstacle height. We reasoned that small deviations in the robot’s initial state and deviations from the planned operational space trajectory would determine whether the robot contacts the obstacle. In turn, contact with the obstacle would yield bifurcations in the final state.

![Virtual Links robot stepping over (top) or into (bottom) an obstacle given high and low step heights, respectively.](image3)

**Fig. 3.** A time-lapse of the virtual *Links* robot stepping over (top) or into (bottom) an obstacle given high and low step heights, respectively.

In the experiment, we directed the robot to step over the obstacles with one of three preset-step-heights. With one step height setting, the robot is able to step over the obstacle only occasionally. The grazing or near-miss event forces the robot using this step height into two distinct clusters of states: ones that correspond to clearing the obstacle and ones that do not (see Figure 4). As the distribution of the green paths in Figure 4 indicates, the sampling strategy makes the grazing bifurcation readily identifiable. A time-lapse depiction of the diverging behavior is shown in Figure 3.

We expect that we would be uncertain as to how the real robot would behave in this situation. This demonstration supports our observation.

**IV. Future Work**

We will soon attempt to replicate the divergent behavior presented in this abstract during in situ experiments to test hypotheses that follow from our observation. We will also determine the minimum magnitude of modeling errors that can cause divergent behavior on simple locomotion systems (e.g. a compass walker) that have been verified with formal methods.

**REFERENCES**


