State Estimation for Legged Robots in Unstructured Terrains

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SUMMARY

In this study, we propose an optimization based moving horizon state estimation (MHE) framework that effectively handles contact transitions of legged robots. We show that current Kalman filter state estimators are not sufficient for the fast and discontinuous dynamics of legged locomotion. We believe MHE framework that explicitly handles dynamics, states, and controls in the presence of contact is a potential solution to these shortcomings. This formulation is structurally similar to multi-phase hybrid trajectory optimization.

I. MOTIVATION

The recent advancements in mobility of legged robots have opened up various real-world applications, where they are required to reliably traverse through unstructured terrains. Accurate robot state estimation through intermittent contact is essential for both control and planning in such environments. Traditional Kalman filter approaches make restrictive assumptions about the noise distributions, are highly sensitive to measurement outliers, and do not explicitly handle discontinuous dynamics of hybrid systems [1]. We believe a contact-aware MHE framework for state estimation may be a potential solution for these shortcomings given recent computational advances and the developments of state of the art solvers capable of solving constrained non-linear programs (NLPs) in milliseconds.

II. METHODOLOGY

The MHE problem is the dual of model predictive control (MPC), but backwards in time. The terminal cost in the MPC is replaced with an arrival cost that summarizes the past state information up to the current state. The key point of this research is the treatment of discontinuous dynamics during impact events. Specifically, once an impact event is detected (indicated by a leg momentum observer signal), the state transition is computed through the hybrid reset map instead of integrating the continuous dynamics. We rely on the assumptions of short and plastic impact as well as known (approximate) time of impact in our formulation.

III. RESULTS AND DISCUSSIONS

Traditional state estimation techniques assume that the system dynamics are continuous and also characterize noises as Gaussian. However, legged robots experience leg and body impacts that violate these assumptions.

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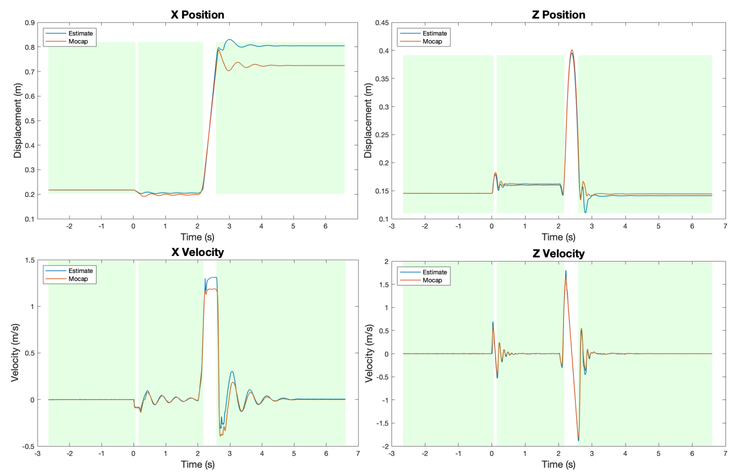

Fig. 1: State Estimation with EKF tracks poorly through impact

Figure 1 demonstrates the shortcomings of the Kalman filter when the system dynamics can switch modes [2]. Minor (~ 5 ms) errors in contact detection timing cause sizeable errors in the state estimate because the EKF does not provide a means to account for error in that dimension.

We propose that an estimator that explicitly handles impact events would perform better on the inherently hybrid nature of legged robot dynamics. We demonstrate that allowing the dynamics model to be a function of the current contact status can improve estimation on a simple double pendulum event-based simulation with plastic ground impact.

Our next step is to implement the moving horizon estimation framework using the contact-dependent nonlinear dynamics of a quadrupedal robot with the differential kinematics of the legs in contact as measurements. We hope to leverage the real-time iteration (RTI) scheme employed by ACADO toolkit [3] to solve the finite-horizon constrained nonlinear problem online.

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