CAREER: A Hybrid Filtering and Robust Control Framework for Legged Robot Locomotion on Dynamic Rigid Surfaces

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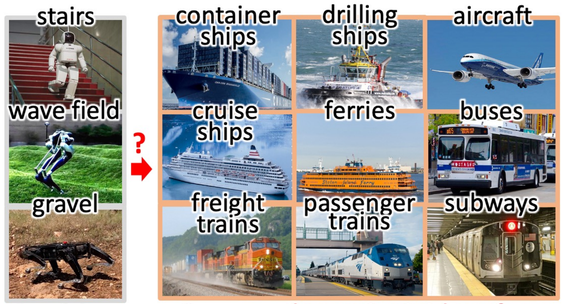
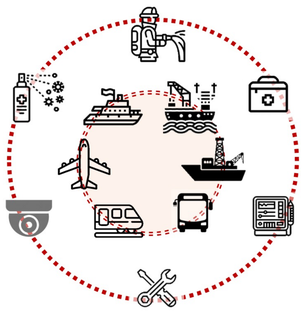
Project URL: https://www.nsf.gov/awardsearch/showAward?AWD_ID=2046562&HistoricalAwards=false

Research Goal: *To create a model-based control framework that produces provably stable legged locomotion on a dynamic rigid surface, drawing upon nonlinear control theory, hybrid systems theory, dynamics, and optimization.*

Broader Impact on Society

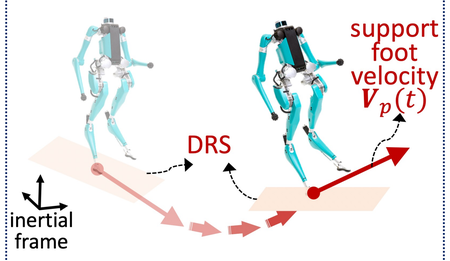


Legged locomotion on a DRS is a new robot functionality



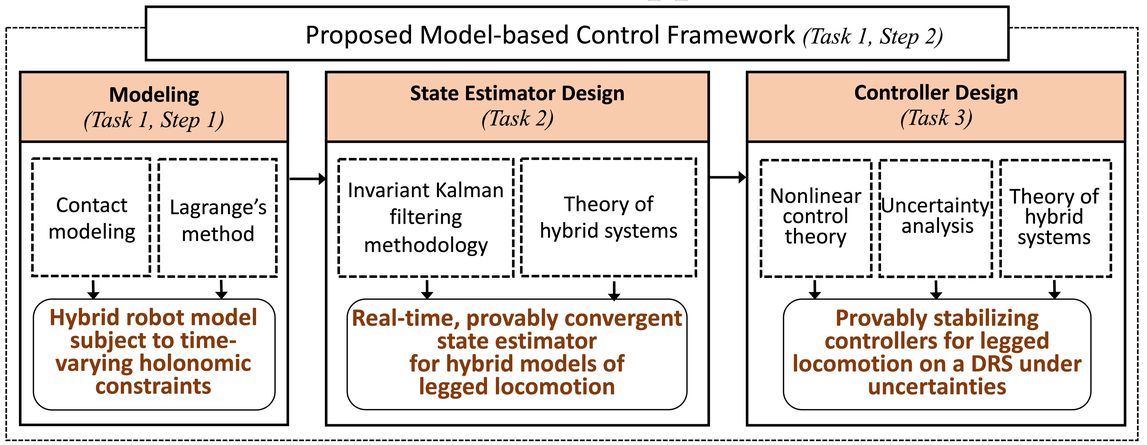
Applications

Challenge



Hybrid, time-varying robot dynamics

Technical Approach



Key Innovations

Provably stabilizing control for hybrid time-varying dynamics

Continuous-phase dynamics:

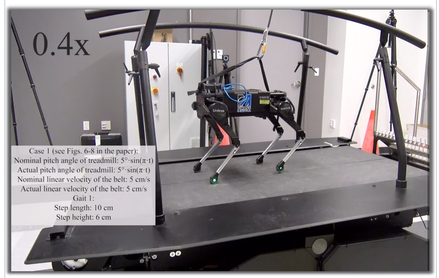
$$\begin{cases} M\ddot{q} + h(q,\dot{q}) = J^T F + Bu \\ J\ddot{q} + \dot{J}\dot{q} = A_p(t) \end{cases}, \quad \text{if } (t,q,\dot{q}) \notin S$$

Landing-impact dynamics (i.e., state-triggered jumps):

$$\begin{bmatrix} q^+ \\ \dot{q}^+ \end{bmatrix} = \Delta(q^-, \dot{q}^-, V_p^+), \quad \text{if } (t,q,\dot{q}) \in S$$

Foot-landing event:

$$S := \{t, q, \dot{q}:\ h_{sw}(t,q) = 0, \dot{h}_{sw}(t,q,\dot{q}) < 0\}$$



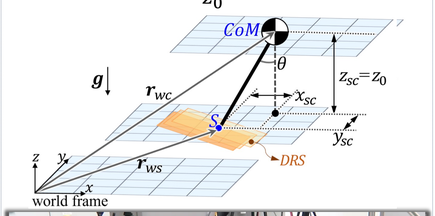
(A. Iqbal, Y. Gao, Y. Gu, IEEE/ASME T-MECH, 2020.)

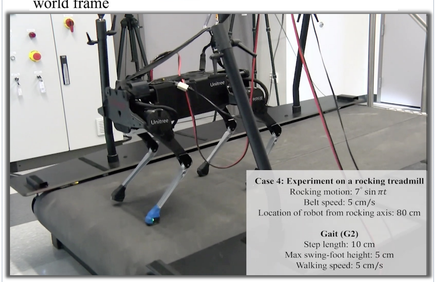
Linear inverted pendulum (LIP) model for DRS locomotion

DRS-LIP:

$$\ddot{x}_{sc} - \frac{(\ddot{z}_{ws} + g)}{z_0} x_{sc} = 0$$

$$\ddot{y}_{sc} - \frac{(\ddot{z}_{ws} + g)}{z_0} y_{sc} = 0$$

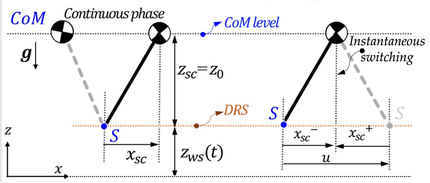




(A. Iqbal, S. Veer, Y. Gu, under review.)

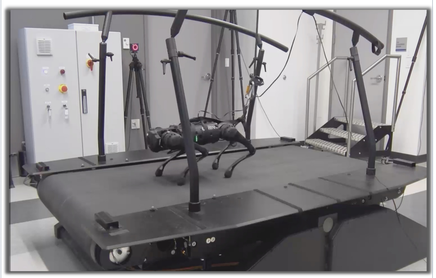
Robust Locomotion under Uncertain DRS motion

Hybrid, time-varying LIP:



Robust stability conditions:

$$\| \bar{\mathbf{A}}_{d,n} \|_\infty < 1$$



(A. Iqbal, S. Veer, Y. Gu, manuscript in preparation.)

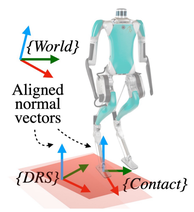
Hybrid invariant filtering

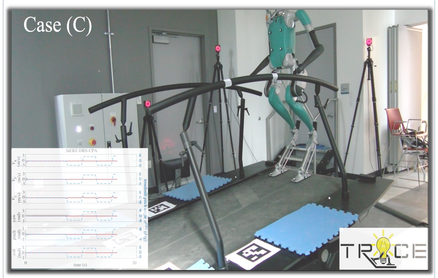
Right-invariant observation:

$$\begin{bmatrix} h_R(\tilde{q}_t) \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\ \mathbf{0}_{3\times 1} \end{bmatrix} = X_t^{-1} \begin{bmatrix} \tilde{R}_t^{DRS}(\tilde{q}_t) \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} \\ \mathbf{0}_{3\times 1} \end{bmatrix} + V_{1,t}$$

Identity error jump map:

$$\Delta(X_1 X_2) = X_1 \Delta(X_2)$$
$$\Delta(X_1 X_2) = \Delta(X_1) X_2$$





(Y. Gao, C. Yuan, Y. Gu, IEEE/ASME T-MECH. 2022.)

Scientific Impact

- Revealed hybrid time-varying robot dynamics in DRS locomotion.
- Expanded leg odometry from static to moving surfaces.
- Created provably stabilizing control methods for DRS locomotion.
- Findings applicable to wheeled/tracked robots and dynamic deformable surfaces.

Outreach and Education

- Enhanced UML's robotics curriculum.
- Presented live demos at Boston Robot Block Party and Purdue's Women in Mechanical Engineering Symposium.
- Mentored six underrepresented minority and female undergraduates in robotics research.

Award ID#: CMMI- 2046562