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

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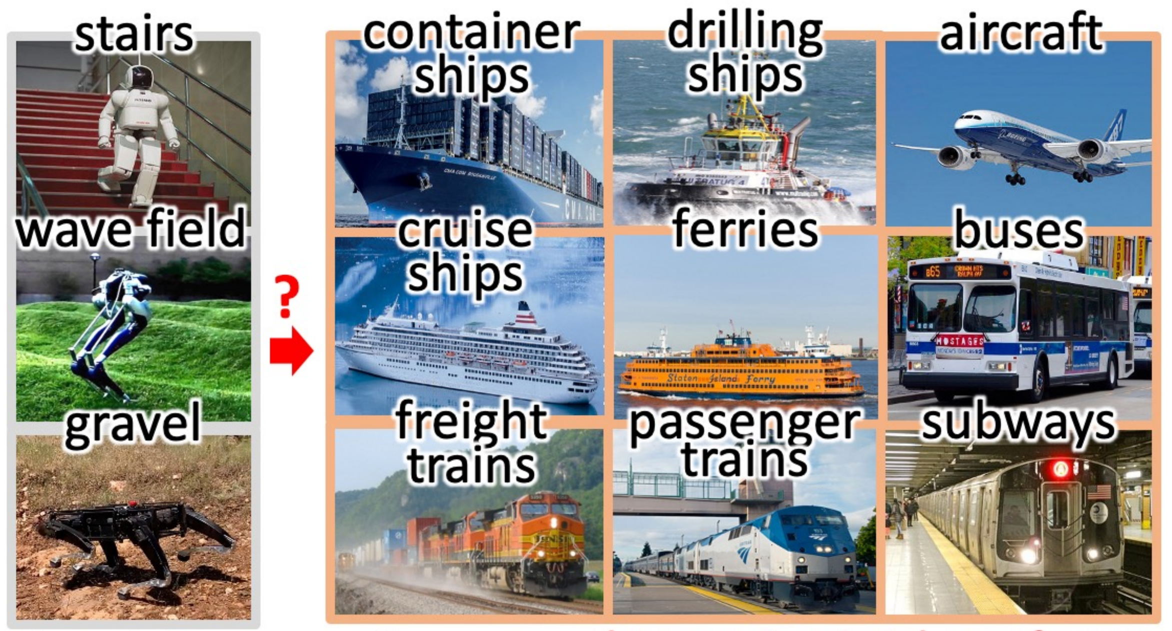
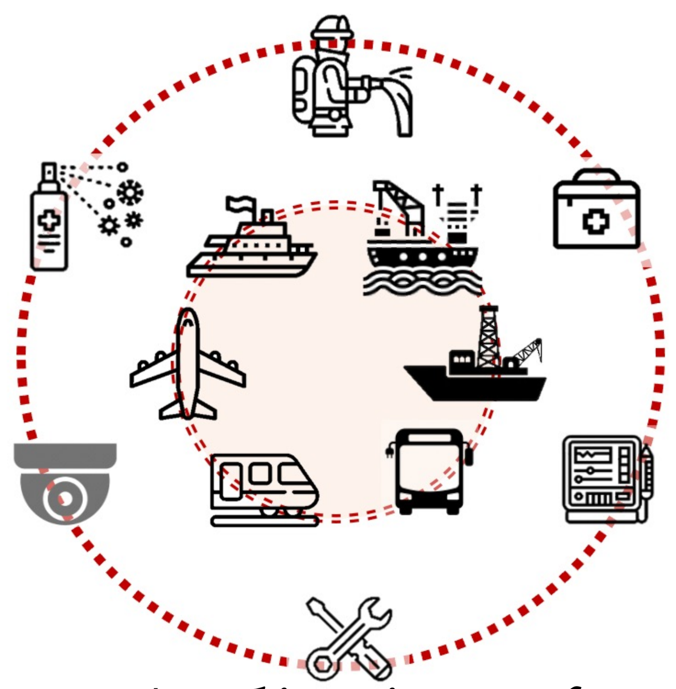
Project URL: https://www.nsf.gov/awardsearch/showAward?AWD_ID=2046562&HistoricalAwards=false

Research Goal: *To draw upon modeling, state estimation, feedback control, and theory of hybrid systems to create a model-based control framework that produces provably stable locomotion on a dynamic rigid surface (DRS).*

Broader Impact on Society

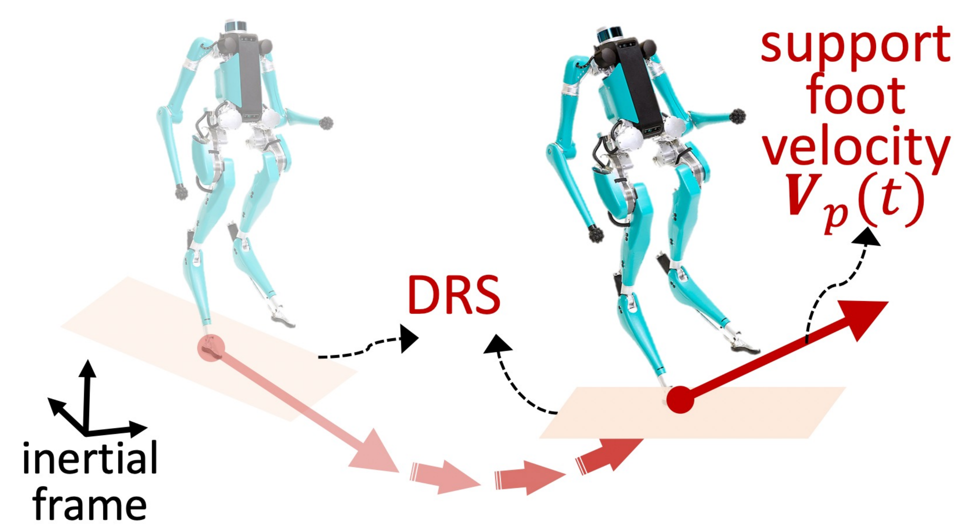


Legged locomotion on a DRS is a new robot functionality



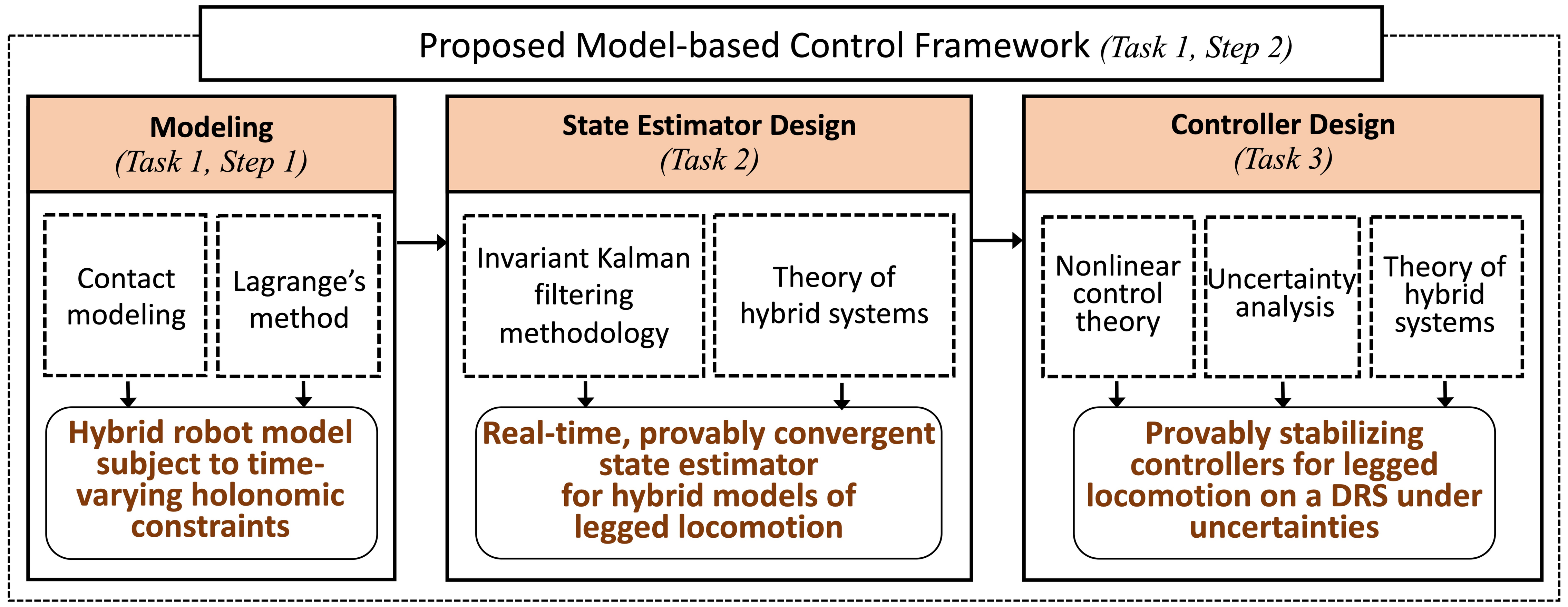
Applications of DRS locomotion

Challenge



Hybrid, time-varying robot dynamics

Technical Approach



Key Innovations

Provably stabilizing control for hybrid time-varying dynamics

Continuous-phase dynamics:

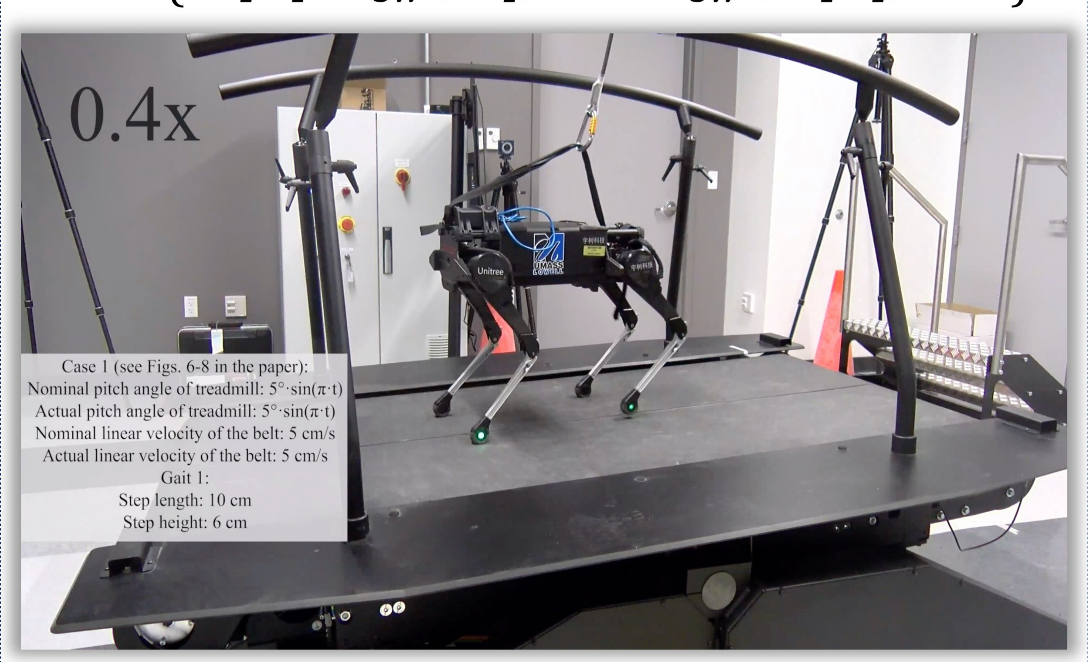
$$\begin{cases} M\ddot{q} + h(q,\dot{q}) = J^T F + Bu \\ J\ddot{q} + \dot{J}\dot{q} = A_p(t) \end{cases}, \quad \text{if } (t,q,\dot{q}) \notin S$$

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:

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



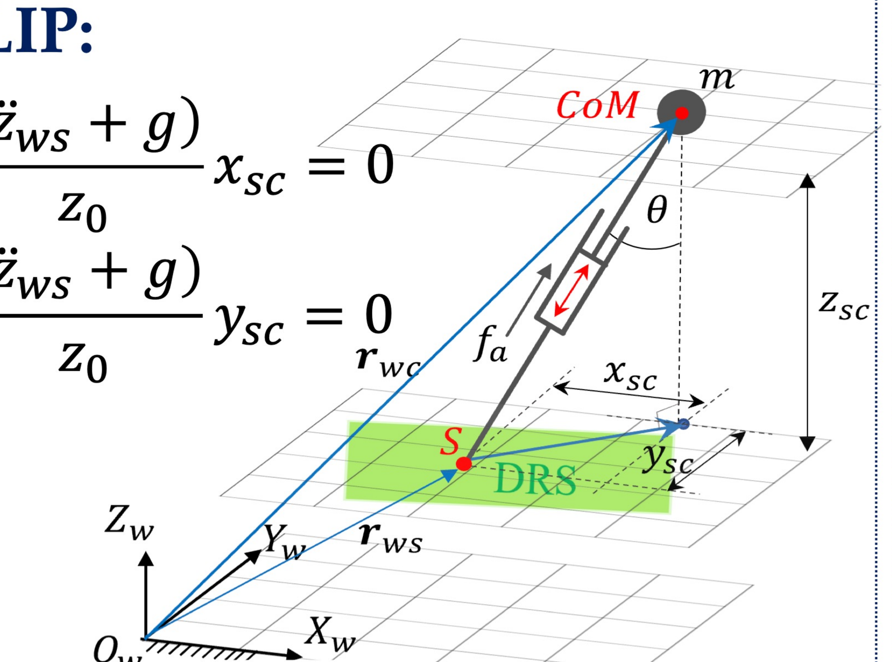
(*Preliminary work*: A. Iqbal, Y. Gao, Y. Gu, IEEE TMECH, 2020.)

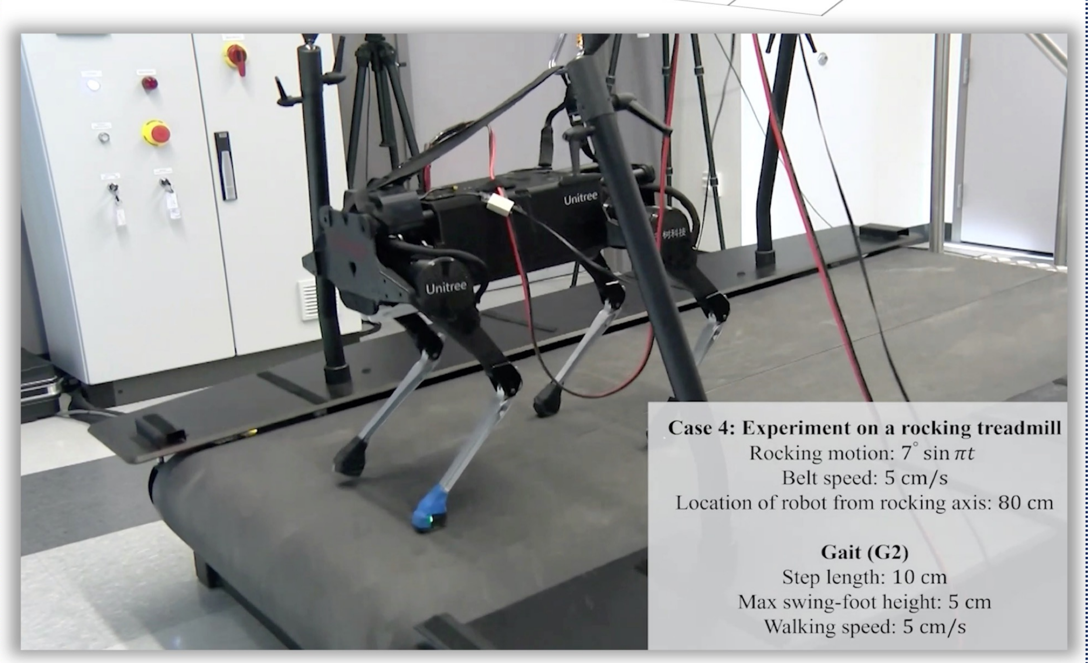
Linear inverted pendulum (LIP) model for DRS locomotion

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, IFAC MECC 2021 & manuscript in preparation.)

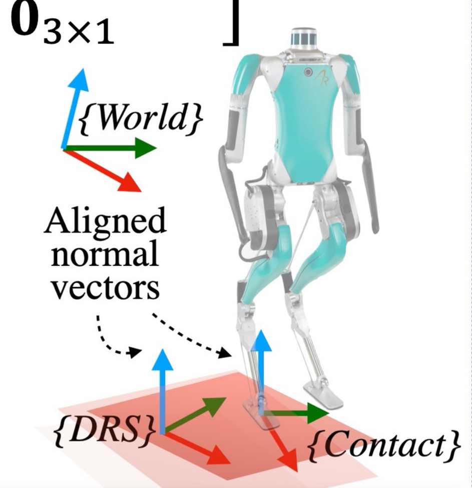
Hybrid invariant filtering

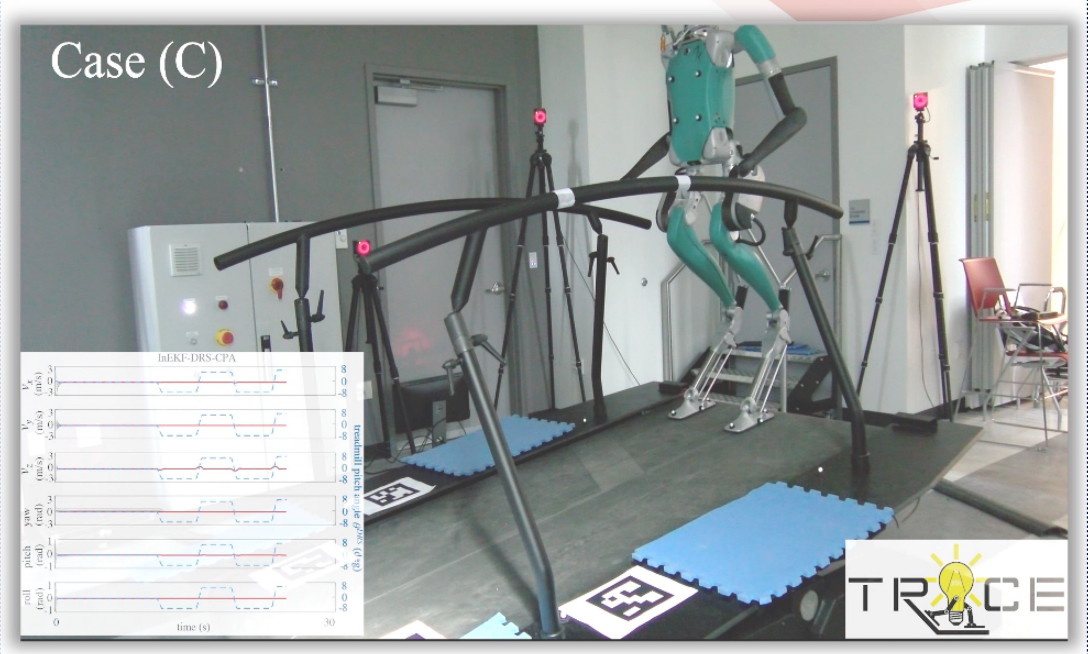
Right-invariant observation:

$$\begin{bmatrix} h_R(\tilde{q}_t)\begin{bmatrix}0\\0\\1\end{bmatrix} \\ 0_{3\times1} \end{bmatrix} = X_t^{-1} \begin{bmatrix} \tilde{R}_t^{DRS}(\tilde{q}_t)\begin{bmatrix}0\\0\\1\end{bmatrix} \\ 0_{3\times1} \end{bmatrix} + V_{1,t}$$

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, IFAC MECC 2021 & manuscript under review.)

Scientific Impact

The research outcomes could be generalized to dynamic deformable surfaces (e.g., tree branches and sea ice), as well as to autonomous locomotion on nonstationary (rigid or deformable) surfaces.

Outreach and Education

- Strengthening UML's robotics curriculum.
- Regional outreach to K-12 students and general public.
- Providing research experiences for five undergraduate underrepresented minority and female students.