Contact/Tracking Control with Impulse-Momentum Sliding Surface and Terminal Sliding Mode

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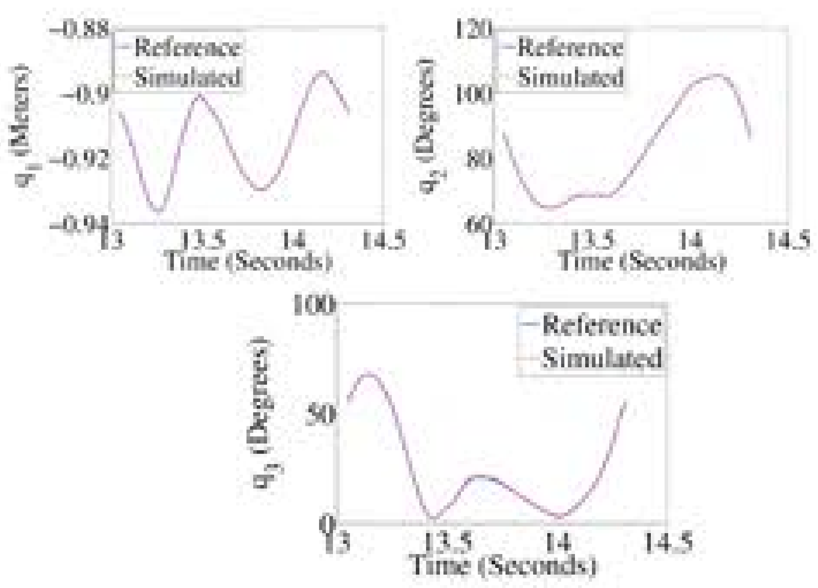
Human-Machine Systems Development Pathway

Concepts



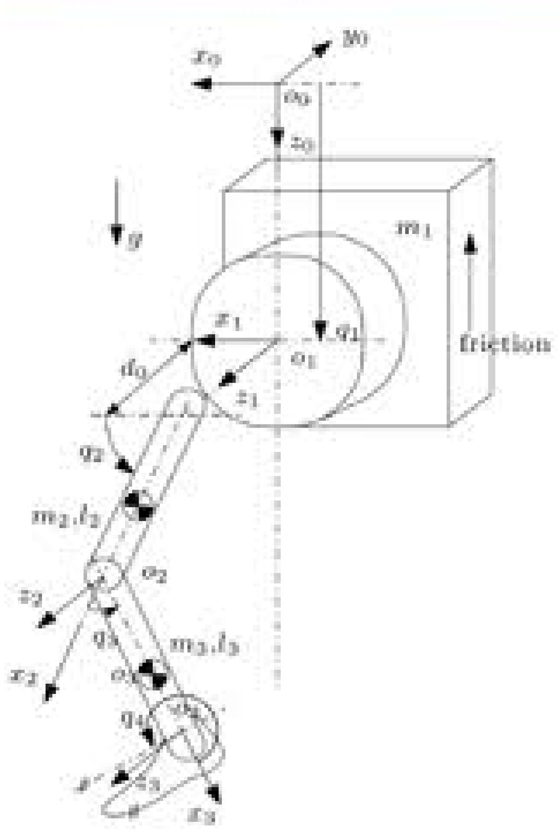
Simulations

Robotic Tests

Bent-Knee Adaptor Tests

Tests with Amputees

CSU Prosthesis Test Robot



- Built for Cleveland Clinic's hydraulic prosthesis tests
- Two degrees of freedom
  - Hip vertical displacement q_1
  - Thigh rotation q_2
- Prosthesis under study, q_3 and q_4, uses its own controller
- Robot controlled with sliding mode control (SMC) for robust tracking, contact and off-contact
- **Allows testing of design and control concepts with safety and repeatability**

Objective

To track reference data recorded from able-bodied gait while off-contact (swing) and ***reproduce patient weight distribution during ground contact (stance)***

Tracking: Terminal SMC

- Used when off-contact, tracking is desired
- "Conventional" SMC achieves $s = 0$ in finite time, but error converges *asymptotically* to zero

$$s_1 = \dot{e} + \lambda e = 0$$

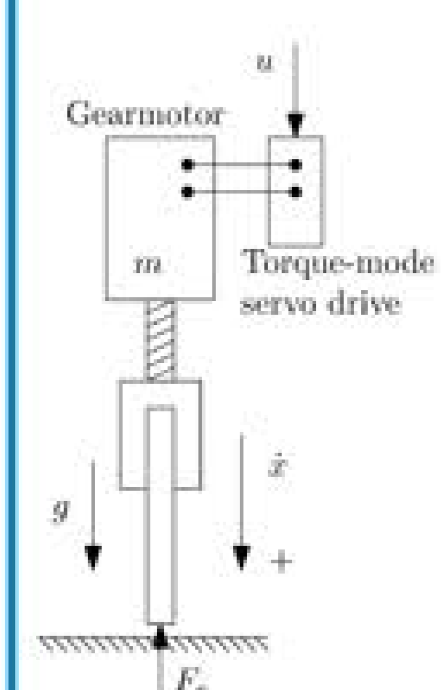
- TSMC uses nonlinear, non-smooth differential equations for the error in the sliding mode

$$s_0 = \dot{e} + \varphi e + \mu e^{\gamma} = 0$$

- When $\gamma < 1$ is rational and $\varphi > 0$, e reaches zero in finite time
- Known finite convergence time is convenient for switching between controllers

Contact: Impulse-Momentum SMC

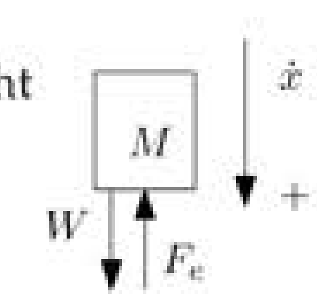
- *Idea*: Control the vertical axis to emulate momentum exchange between a virtual mass/weight and a compliant environment (treadmill belt)
- Contact controller must reproduce the virtual mass and weight *robustly*.
- The approach can also produce virtual environment properties such as damping



Electromechanical model with uncertainties and environmental force input

$$m\ddot{x} + \delta(x, \dot{x}) = ku - F_e$$

Target contact dynamics: new mass/weight interacting with environment through F_e



$$M\ddot{x} = -F_e + W$$

- With a mostly elastic environment (treadmill belt $K \approx 37,000$ N/m) high bouncing will occur. Must add damping by virtual means $M\ddot{x} = -F_e + W - B\dot{x}$
- Sliding surface is

$$s_1 = M\dot{x} + Bx + \int_{t_I}^{t} (F_e(\tau) - W)d\tau - M\dot{x}(t_I) - Bx(t_I)$$

- The integral and the impact position and velocity must be reset when the contact-mode controller is switched in
- Reaching condition $\dot{s}_1 = -\eta \operatorname{sign}(s_1), \eta > 0$ results in

$$u_1 = -\frac{1}{k}\left[r(\eta_1 \operatorname{sign}(s_1) - W) + (r-1)F_e + (Br - b)\dot{x}\right]$$

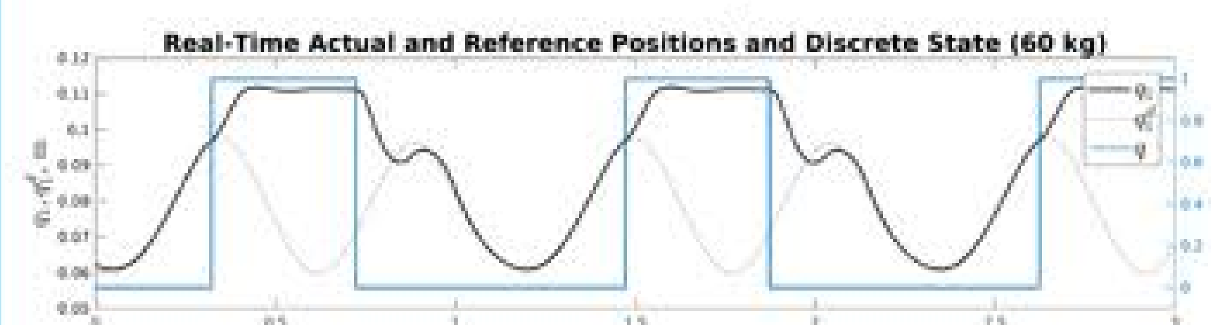
Control Switching

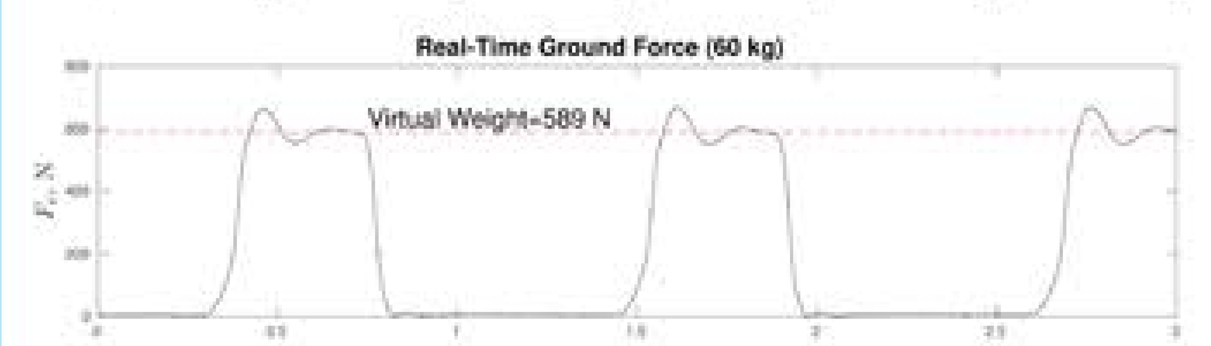
- Use TSMC for off-contact tracking of hip trajectories
- Use IM-SMC during contact
- Discrete states: $q = 0$ (off-contact), $q = 1$ (contact)
- Force-based rule inadequate due to bouncing, chattering, or inability to switch at all

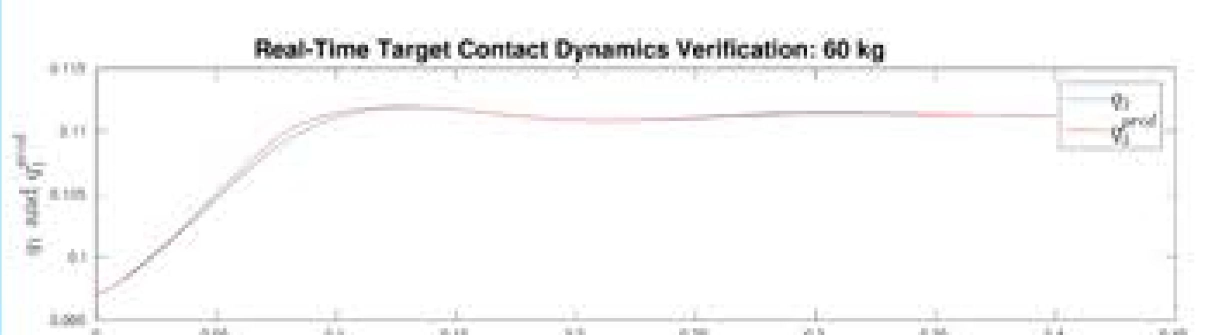
$\Rightarrow$ Switch according to force threshold and dwell times

Real-Time Test Results

Test Conditions: $M = 60$ kg, $B = 2500$ Ns/m







Conclusions

- Control law successfully applied to vertical displacement alone, no thigh rotation
- Maximum error between actual and predicted velocities is 3.8% for 60 kg mass
- Approach simple and effective for machine emulation of patient weight

Continuing Work

- Operate hip displacement under the developed switched controller and thigh rotation under a SMC for tracking
- Activate prosthesis degrees of freedom
- Determine an asynchronous controller switching law for walking
- Use thigh periodicity and/or other sensors as clock
- Proposed discrete switching law:

$$q^+ = \begin{cases} 1, & F_e > F_{th} \text{ and } q_2 < \frac{\pi}{2} \\ 0, & \ddot{q}_2^d < \ddot{q}_{2,th}^d \text{ and } q_2 > \frac{\pi}{2} \\ q, & \text{otherwise} \end{cases}$$

Reference

Richter, H., Mobayen, S., & Simon, D., 2018. Contact/Tracking Control with Impulse-Momentum Sliding Surface and Terminal Sliding Mode. In ASME 2018 Dynamic Systems and Control Conference.

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