CONTACT/TRACKING CONTROL WITH IMPULSE-MOMENTUM SLIDING SURFACE AND TERMINAL SLIDING MODE

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HUMAN-MACHINE SYSTEMS DEVELOPMENT PATHWAY

CSU PROSTHESIS TEST ROBOT
- Built for Cleveland Clinic’s hydraulic prosthesis tests
- Two degrees of freedom
  - Hip: vertical displacement q₁
  - Thigh rotation q₂
- Prosthesis under study, q₁ and q₂, 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)

CONTACT: IMPULSE-MOMENTUM SMC
- Idea: Control the vertical axis to emulate momentum exchange between a virtual mass/weight and a compliant environment (treadmill belt)
- 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

\[ m \ddot{z} + \delta(x, \dot{x}) = ku - F_c \]

Target contact dynamics: new mass/weight interacting with environment through \( F_c \)

\[ M \ddot{z} = -F_c + W \]

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

- Sliding surface is

\[ s_1 = \dot{M}z + Br \int_0^t (F_c(\tau) - W) d\tau - \dot{M}z(t_1) - Br(t_1) \]

- The integral and the impact position and velocity must be reset when the contact-mode controller is switched in

\[ s_1 = -\dot{z} \cdot \text{sign}(s_1), \dot{z} > 0 \text{ results in} \]

\[ u_1 = -\frac{1}{B} \int [r(\eta_1 \cdot \text{sign}(s_1) - W) + (r - 1)F_c + (Br - b \dot{z})] \]

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 rules inadequate due to bouncing, chattering, or inability to switch at all
- Switch according to force threshold and dwell times

REAL-TIME TEST RESULTS

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:

\[ q^* = \begin{cases} 
1, & F_c > F_{th} \text{ and } q_2 < \frac{q_2}{q_2} \\
0, & q_1 < \frac{q_1}{q_1} \text{ and } q_2 > \frac{q_2}{q_2}
\end{cases} \]

REFERENCE

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